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NAVAL UNDERSEA WARFARE CENTER DIVISION
NEWPORT, RHODE ISLAND

Technical Memorandum

PROCEEDINGS OF THE NUWC DIVISION NEWPORT SEMINAR SERIES ON **TURBULENCE AND ITS CONTROL**

1 October 1992

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Weapons Technology and
Undersea Systems Dept.

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NUWC2015 Additional authors: Brown, Garry; Roshko, Anatol

14. ABSTRACT
This memorandum records the proceedings of a four-part seminar series on turbulence and its control sponsored by the Naval Undersea Warfare Center Division, Newport, Rl, during the summer of 1992. The Naval Undersea Warfare Center Division, Newport, RI, organized a four-part seminar series titled Turbulence and Its Control during the summer of 1992 . One seminar was held in June, one in July, and two in August. These seminars were an activity of NUWC's Hydrodynamics Sphere of Excellence, which is one of the Center's leadership areas. The presentation materials used during the seminars, consisting mostly of informal viewgraphs, are reproduced in this report in their original form.

15. SUBJECT TERMS
Turbulence; Hydrodynamics Sphere of Excellence; viscous flow; RNG; renormalization group theory; magnetohydrodynamic method; bluff-body wakes

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ABSTRACT

This memorandum records the proceedings of a four-part seminar series on turbulence and its control sponsored by the Naval Undersea Warfare Center Division, Newport, RI, during the summer of 1992.

ADMINISTRATIVE INFORMATION

This document was prepared by Code 8234 under internal funding.

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FOREWORD

The Naval Undersea Warfare Center Division, Newport, RI, organized a four-part seminar series titled *Turbulence and Its Control* during the summer of 1992. One seminar was held in June, one in July, and two in August. These seminars were an activity of NUWC's *Hydrodynamics Sphere of Excellence,* which is one of the Center's leadership areas. The presentation materials used during the seminars, consisting mostly of informal viewgraphs, are reproduced in this report in their original form.

In the first seminar, Professor Hussain discussed in great depth the viscous flow physics of the numerically simulated "simple" problem of the interaction between two vortices.

In the second seminar, Professor Orzwag presented renormalization group (RNG) theory, which has generated a great deal of interest recently due to its surprising success in the rational calculation of widely different turbulent flows. RNG theory has already been closely scrutinized by many independent groups. In high Reynolds number practical flows, particularly those with strong anisotropy, RNG might become the standard tool.

The third seminar, led by Professors Nosenchuck and Brown, focused on a novel magnetohydrodynamic method of turbulence control. Professor Nosenchuck, with his keen aptitude for application, and Professor Brown, with his deep insight, made a formidable team. The turbulence control they have achieved with minimal power has surpassed that obtained with polymers.

In the fourth and final seminar, Professor Roshko reviewed our understanding of the turbulence in bluff-body wakes -- a topic that has always been of prime interest to him. He discussed his recent works, emphasizing the end-effects in laboratory experiments and highlighting the lack of agreement between so-called two-dimensional measurements and computer simulations.

1. New Aspects of Vortex Dynamics and Hydrodynamic Turbulence

A. K. M. F. Hussain
University of Houston

SEMINAR NOTICE

NEW ASPECTS OF VORTEX DYNAMICS AND HYDRODYNAMIC TURBULENCE

A. K. M. F. Hussain

Cullen Distinguished Professor

University of Houston

We try to shed some light on coherent structures and turbulence phenomena through studies of the new aspects of vortex dynamics, and of coherent vortex interaction with fine scale turbulence. These studies are done by direct numerical simulation of the Navier-Stokes equations. First, we explore the vortex reconnection mechanism and its role in turbulence cascade and mixing. We come to realize that core dynamics is important in reconnection and, although ignored so far, is very important for vortex dynamics. We explain core dynamics first in the framework of traditional quantities as colliding wavepackets resulting from coupling of meridional flow and swirl, and then in the framework of a new mathematical tool - 'complex helical wave decomposition' - which gives a clearer understanding of the flow physics in terms of polarized vorticity waves, expressed in terms of the eigenmodes of the curl operator. Finally, we discuss the symbiotic relationship between coherent structures and incoherent turbulence and question the validity of 'local isotropy' - the centerpiece of Kolmogorov's equilibrium hypothesis and of virtually all theories of turbulence.

Wednesday, 3 June 1992

Conference Room, Bldg. 990 (6th Floor)

Time: 10:30 AM

POC: Dr. Promode R. Bandyopadhyay (Code 804; x2588)

UNDERSTANDING TURBULENCE VIA VORTEX DYNAMICS

Outline

0. Coherent structures & flow visualization.
1. Review Reconnection mechanism
2. Vortex core dynamics/ polarized vorticity
3. Coherent structure/ fine-scale turb. interaction
4. Viscous generation of helicity

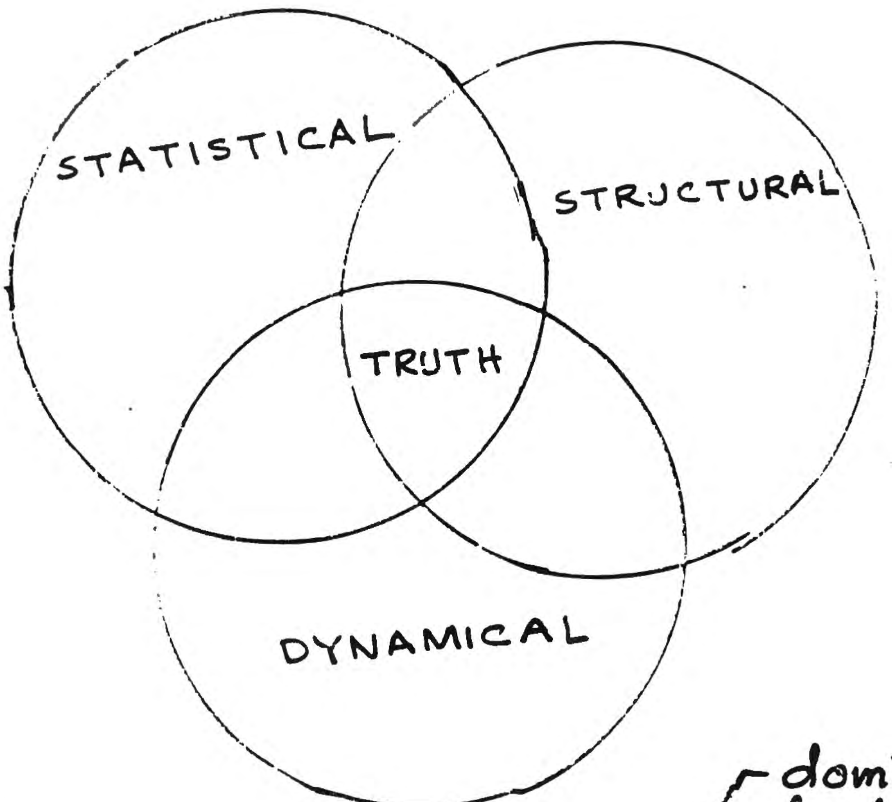
3 Approaches to turbulence

statistical (1940's $\rightarrow$)

structural (1970's $\rightarrow$)

Dynamical (1980's $\rightarrow$)

will not review: mainly mention our ideas



our focus: so far: structural ← dominant features

new: also dynamical } Establish Connectio

structure evolution → statistics

Least understood: LS ↔ fine scal

Coherent Structures (CS)

⇒ Char. feature of Turb. Sh. Flows

TURB. MANAGEMENT (i.e. enhance & suppr.)

via control of: GENERATION
GROWTH
INTERACTION
DECAY
} of CS

POTENTIAL BENEFITS:

FUNDAMENTAL

TECHNOLOGICAL

Extensively studied
No time

Topology ⇐ Definition & Measurement

Roles in Turb. Phenomena (ent., mixing)

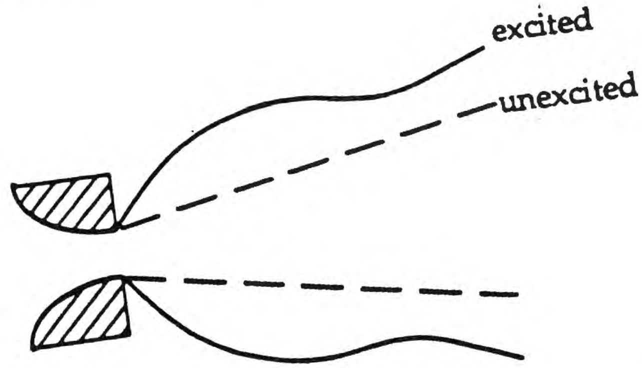
Dynamical Significance

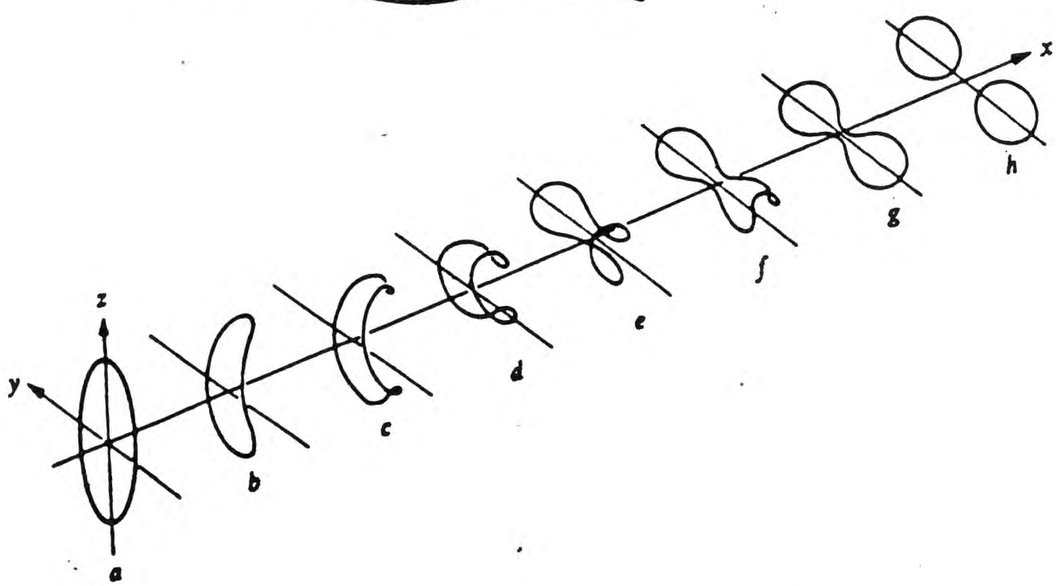
Management of turbulence phenomena?

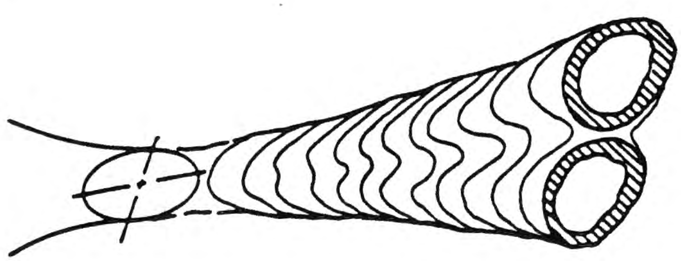
→ Yes, by CS manipulation.

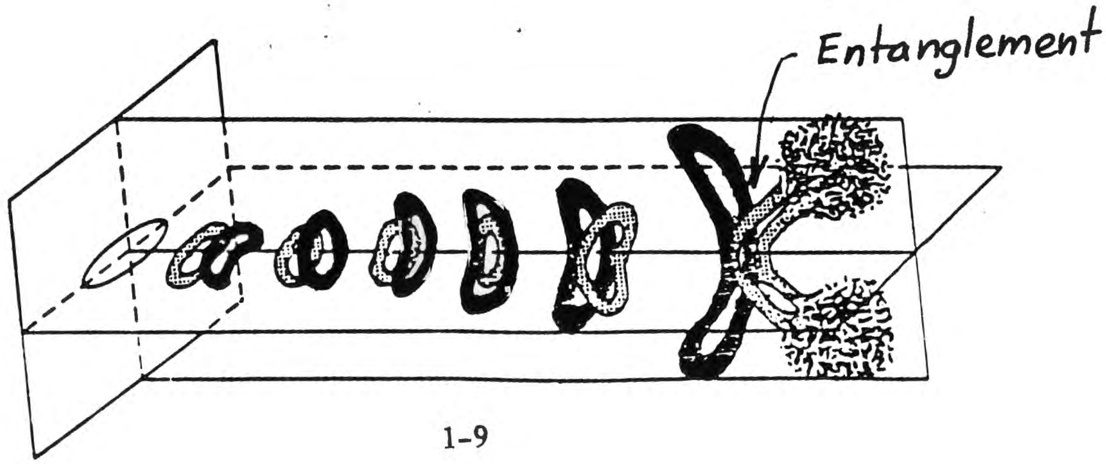
No CS, no control

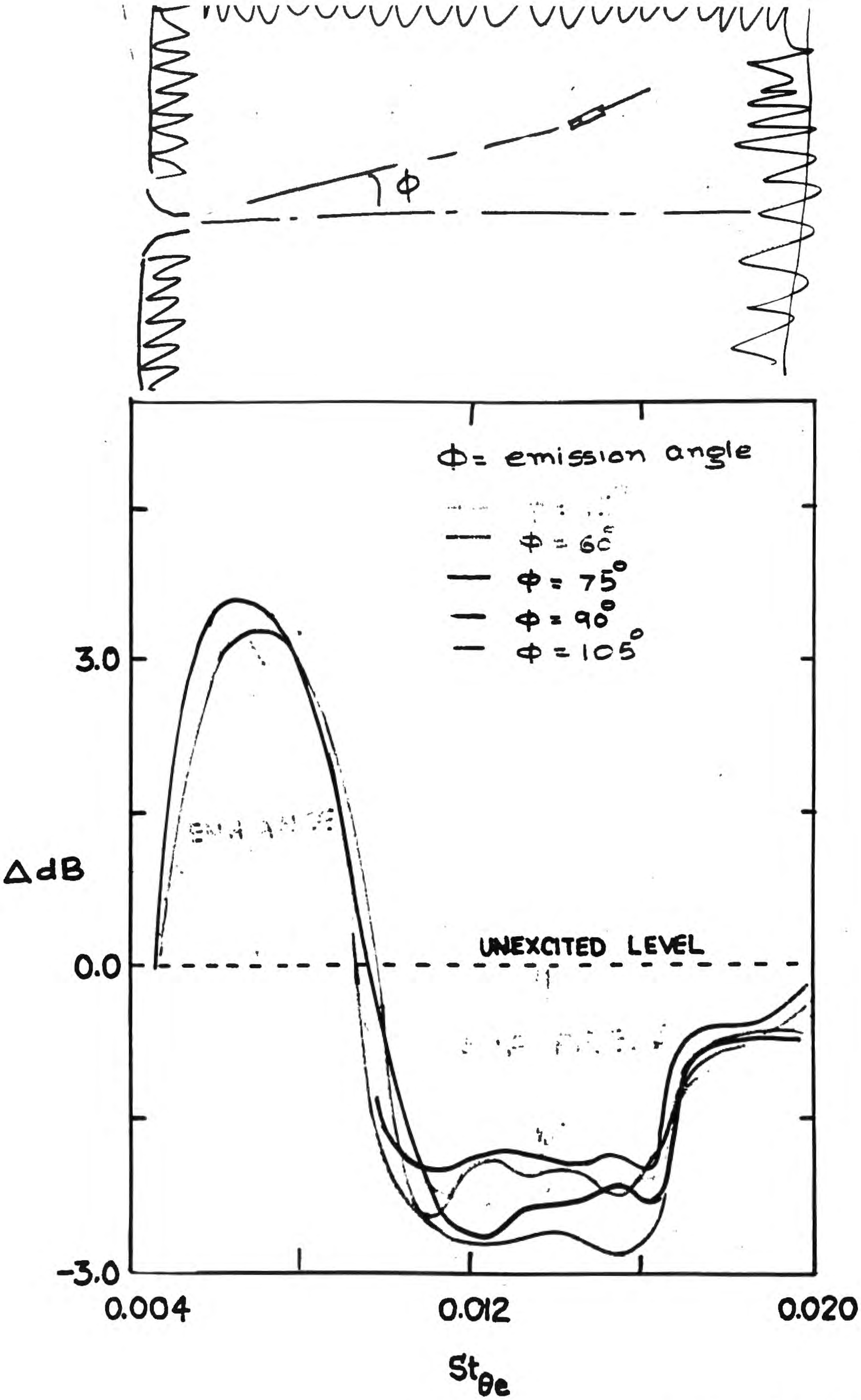
Turb. control: elliptic jet











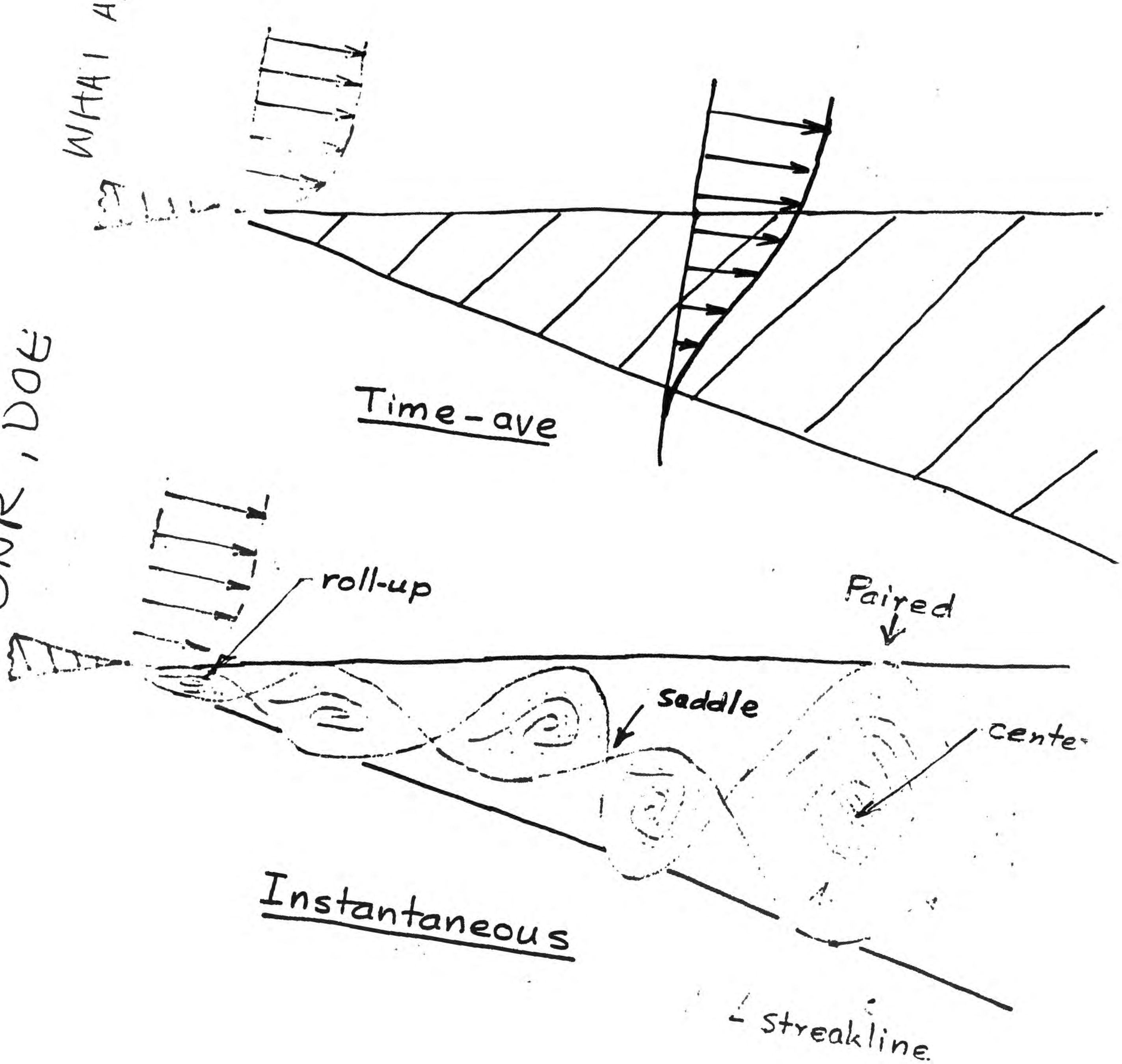
Hussain & H.
JFM (1984)

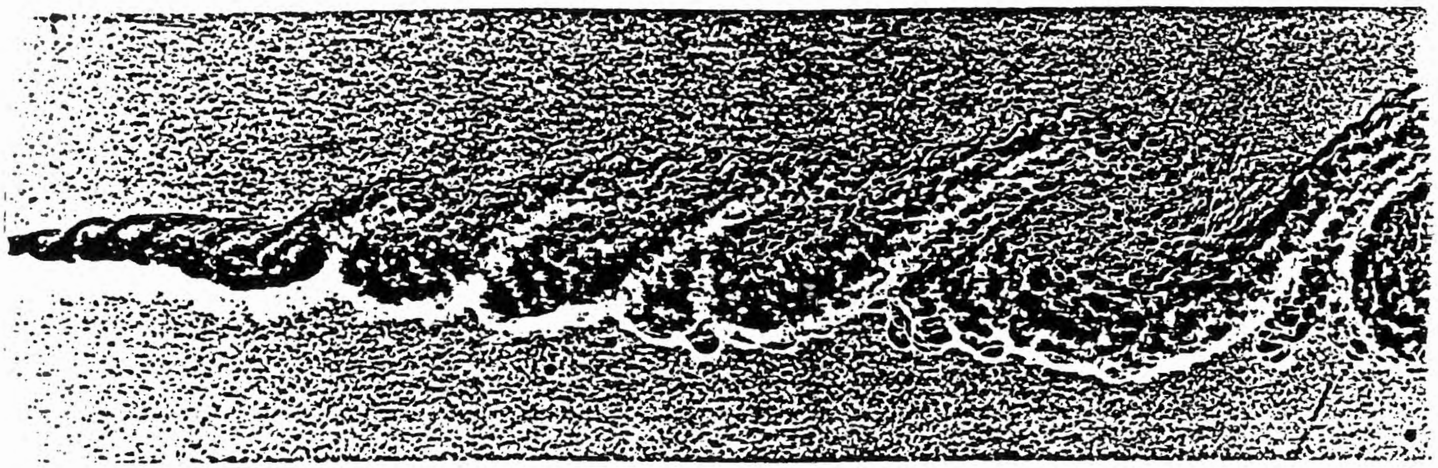
Aerodynamic noise suppression via excitation;
4 cm circular jet; M = 0.15

WHAT ARE CS?

ONR, DOE

Mixing Layer





Brown & Roshko, CalTech

Virtually all studies of CS

FLOW VISUALIZATON

Suffers from Limitations

Mostly confusing (esp. in fully turb. flow)

Can be greatly misleading

Exceptions

Browand & Wiedman (ML)

Cantwell & Coles (Wakes)

Houston Studies (CJ, PJ, EJ, ML, Wak. BL, ChF, HEF, Coml.

Recently Others

$$\frac{D\vec{\omega}}{Dt} = \vec{\omega}\cdot\nabla\vec{u} + \nu\nabla^2\vec{\omega}$$

self-aug. (stretching.

$$\frac{Dc}{Dt} = \mathcal{D}\nabla^2 c$$

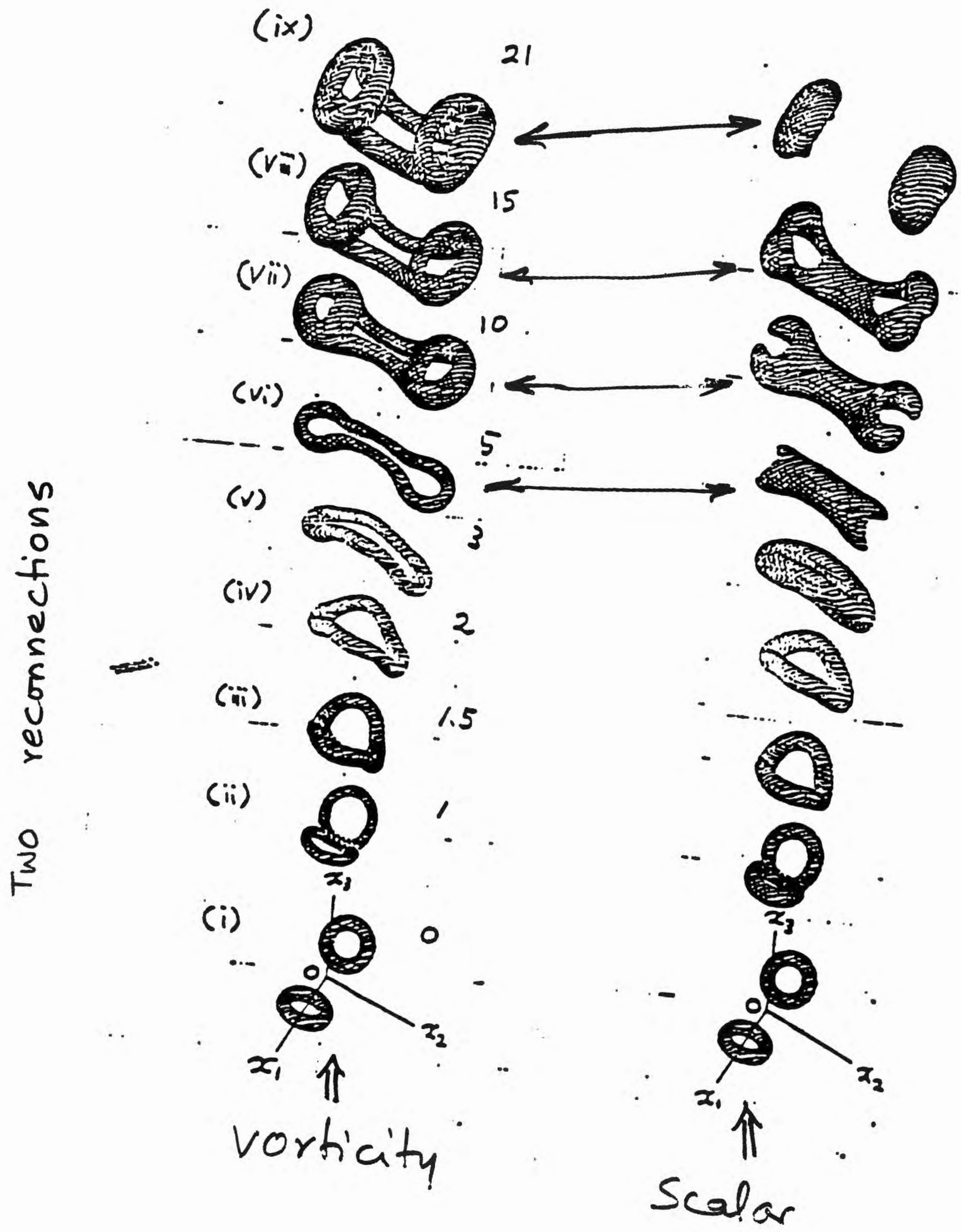
Boundaries of $|\vec{\omega}|$, c same in 2D if $Sc = \frac{\nu}{\mathcal{D}} = 1$

NOT SO in 3D even if $Sc = 1$

Cut & Connect $|\omega|$, c only

XAMPLE

Kida, Takaoka & Hussain (JFM 91)



$Re = \Gamma/\nu = 1000$

Melander & Hussain (88)
Direct Sim.
NASA/Ames

Moffat, H.K. 1985 *J. Fluid Mech.* **159**, 359.
Schatzle, P.R. 1987, PhD thesis, California Institute of Technology.
Siggia, E.D. and Pumir, A. 1985 *Phys. Rev. Lett.* **55**, 1749.
Takaki, R. & Hussain, A.K.M.F. 1985, *Turbulent Shear Flows V*, Springer, 3.19.
Tsinober, A. & Levich, E. 1983 *Phys. Lett. A* **99**, 321.

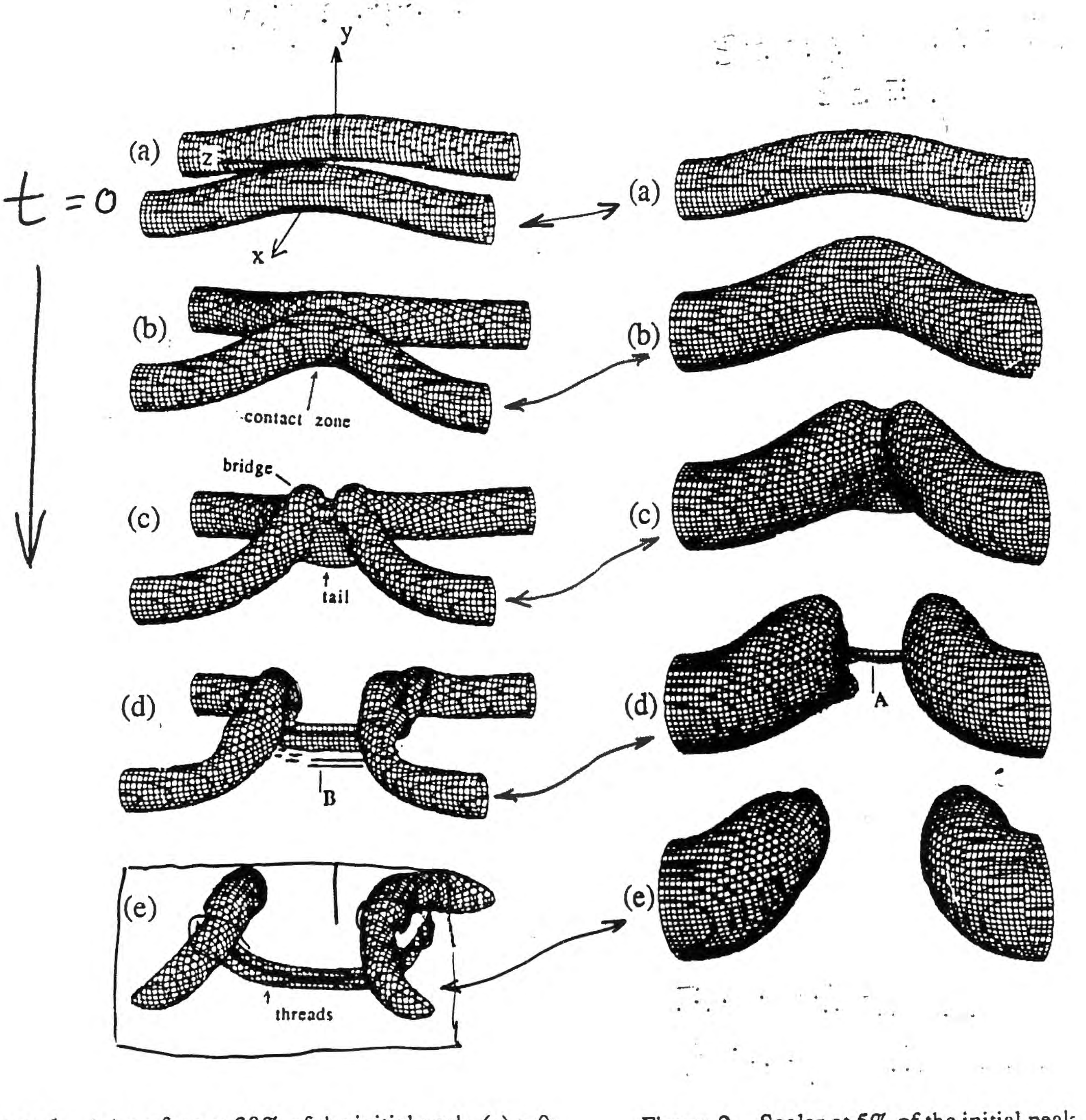
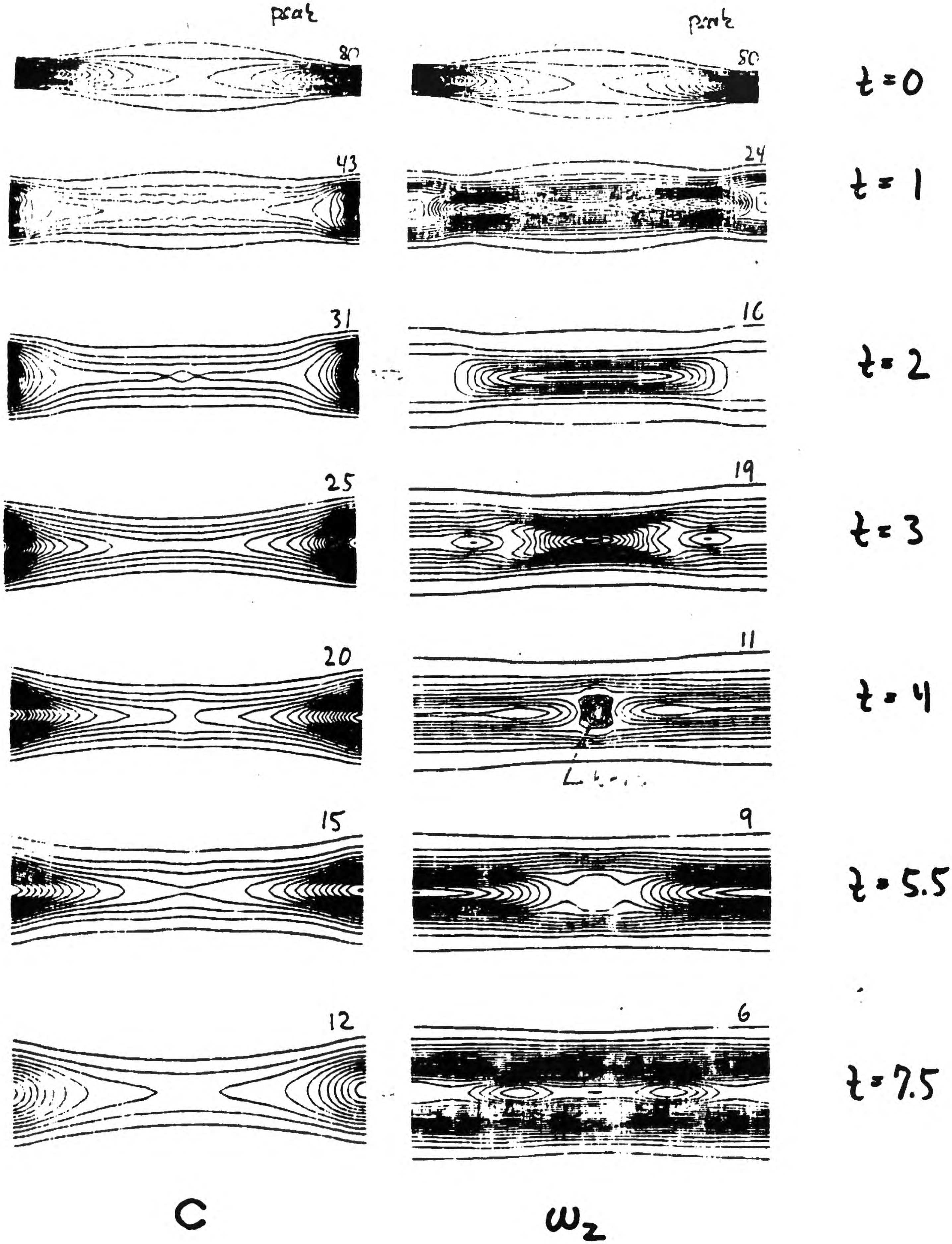


Figure 1. $|\omega|$ surface at 30% of the initial peak. (a) t=0; (b) t=2.25; (c) t=3.5; (d) t=4.75; (e) t=6.0

Figure 2. Scalar at 5% of the initial peak. (a) t=0; (b) t=2.25; (c) t=3.5; (d) t=4.75; (e) t=


peak
peak
80
50
t = 0
43
24
t = 1
31
16
t = 2
25
19
t = 3
20
11
t = 4
15
9
t = 5.5
12
6
t = 7.5
C
ω_z

What are CS?

Definition intensely debated for a decade

Hussain et al. 79, 81, 83, 86, 89

Repeat:

Flow domain with spatially phase-correlated vorticity $\vec{\omega}(\vec{x},t)$

Correlated part of $\vec{\omega}$ ⇐ <u>coherent vorticity</u>

remainder ⇐ <u>incoherent</u> turbulence

EDUCTION extracts CS in turb. flows

discusses: topology
coupling with incoh. turb.
dynamical significance

Defn. of vortex in a turbulent flow

$N_K \geqslant 1$ Kin. Vort. No.

$$N_K \equiv \left[\frac{\omega_k \omega_k}{2 S_{ij} S_{ij}}\right]^{1/2}$$

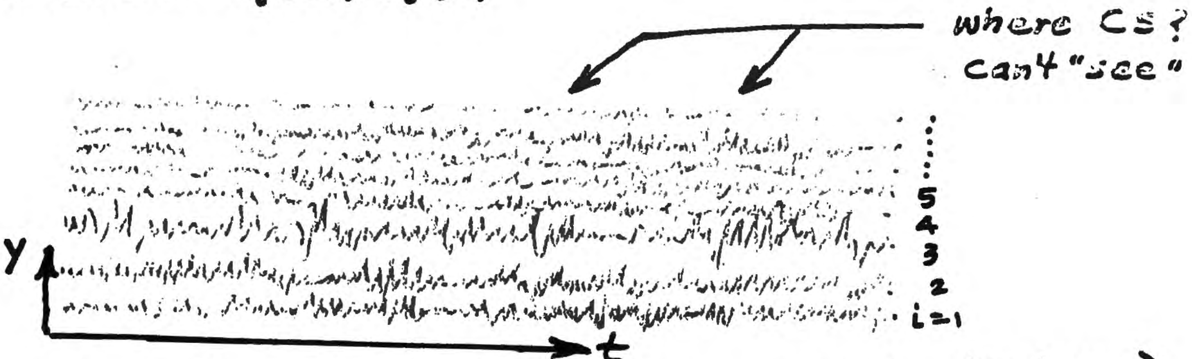
(Truesdell 5:

NOT REVIEW ALL TOPICS & RESULTS

Also in Oceanic or Atmospheric f

1. Place a trans. array of X-wires (or other sensors

2. Obtain $u_i(t), v_i(t)$

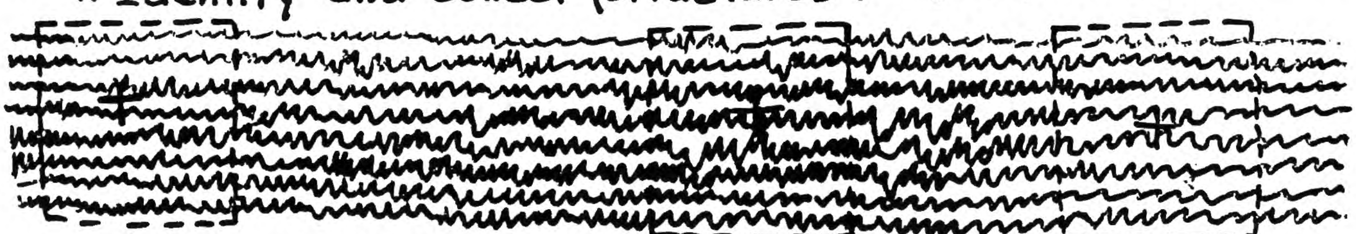


3. Smooth and obtain $\omega(x,y)$ $t \leftrightarrow x$ (T. hyp.)

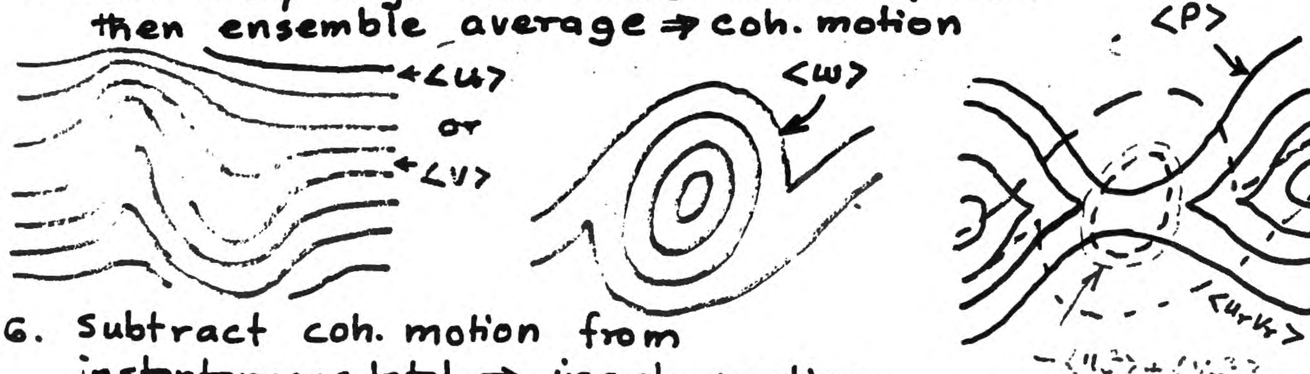
DNS or image ← not nec.

Applied to Num. Sim. also

4. Identify and collect (structures') signals using criteria



5. Iteratively align thru cross-correl. of $\vec{\omega}(\vec{x})$ then ensemble average ⇒ coh. motion



6. Subtract coh. motion from instantaneous total ⇒ incoh. motion

$$u - \langle u \rangle = u_r$$

Quantitative studies of CS

POD (Lumley/Sirovich)

Cond. Eddy (Adrian/Moin)

Our approach: vortex dynamics

(not well dev. for turb. environ.)

1. Defn. of a vortex in turb. flow

J. Jeong

2. Evolutionary dynamics in turb.

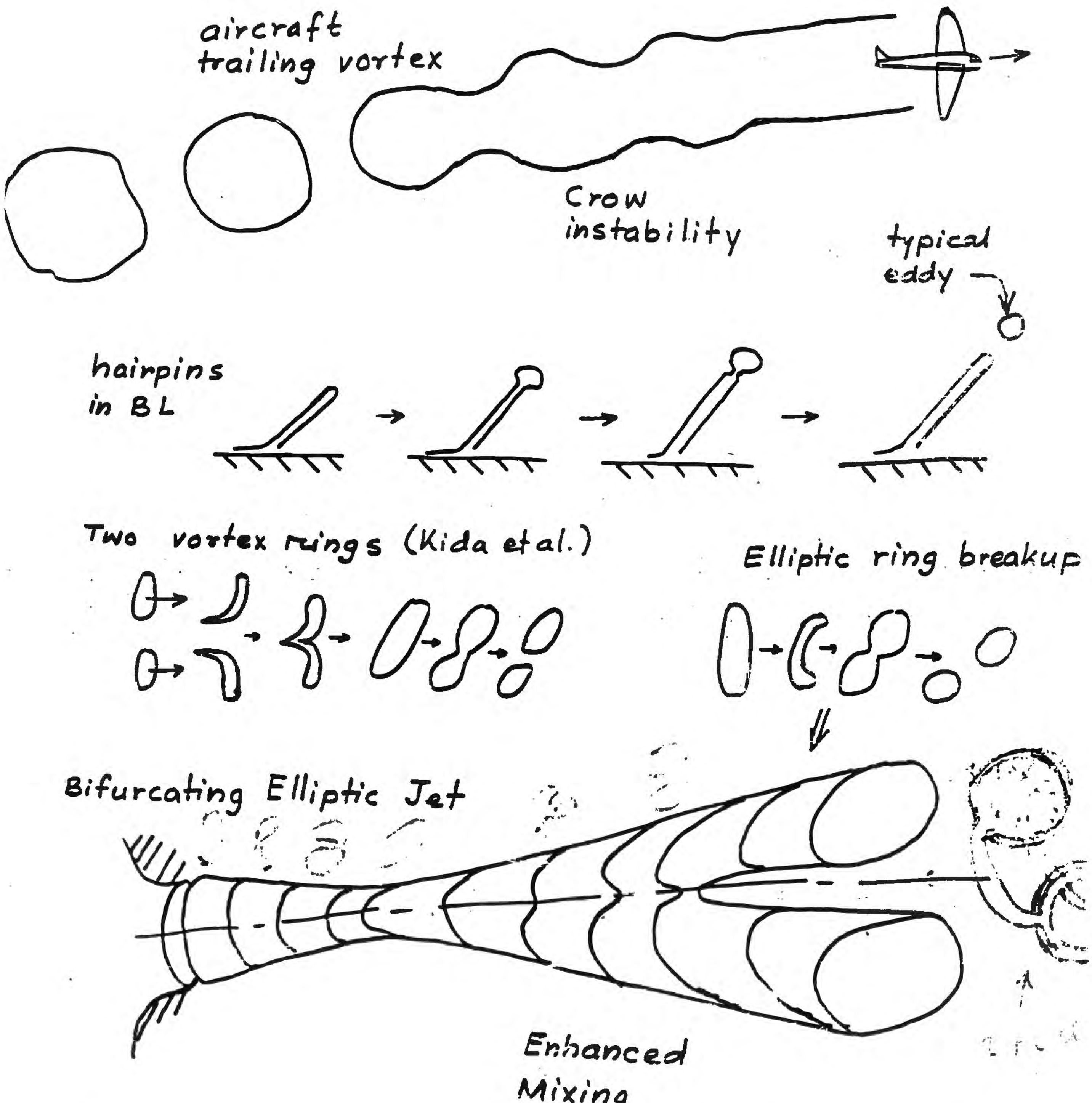
a. Vortex reconnection

b. Vortex/turbulence (fine-scale) interactio

M. V. Melander

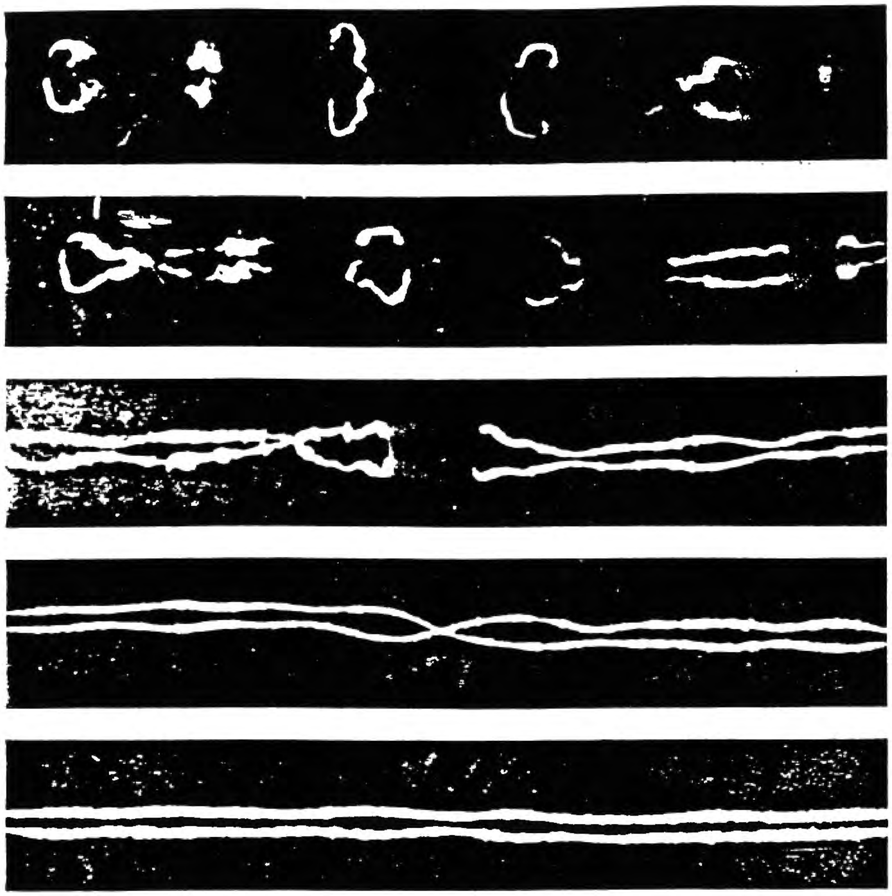
D. Virk

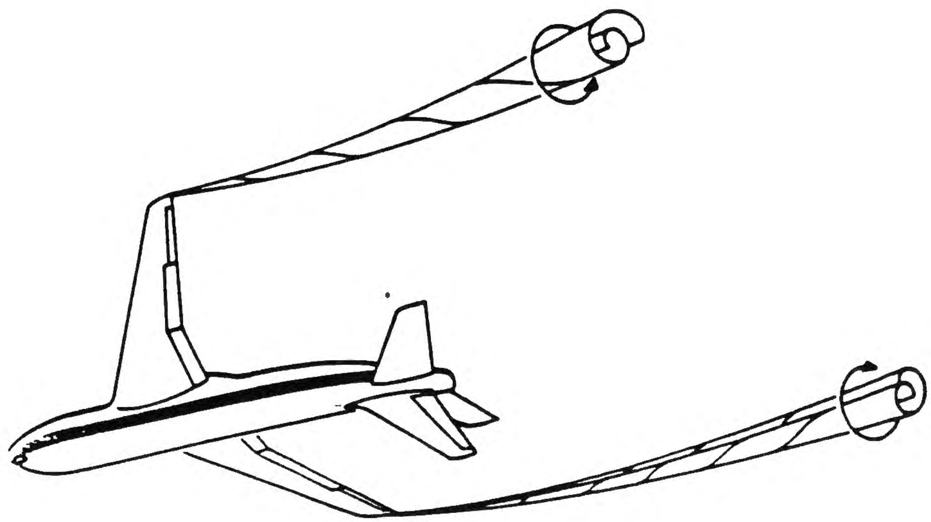
Some examples of reconnection



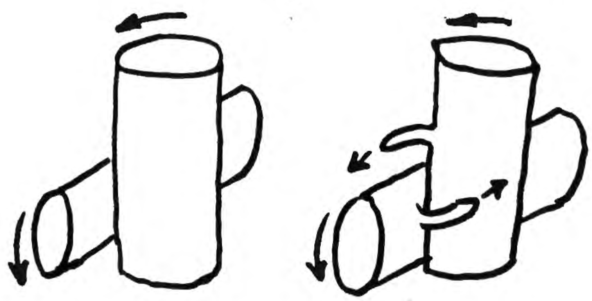
Also
JFM (89)

HUSAIN & HUSSAIN (1983)
also in Liepmann & Narasimha (88)





Reconnection Mechanism



Melander & Zabusky (88)

Hairpins, entanglement

Viscosity unimportant

also Kida & Takaoka

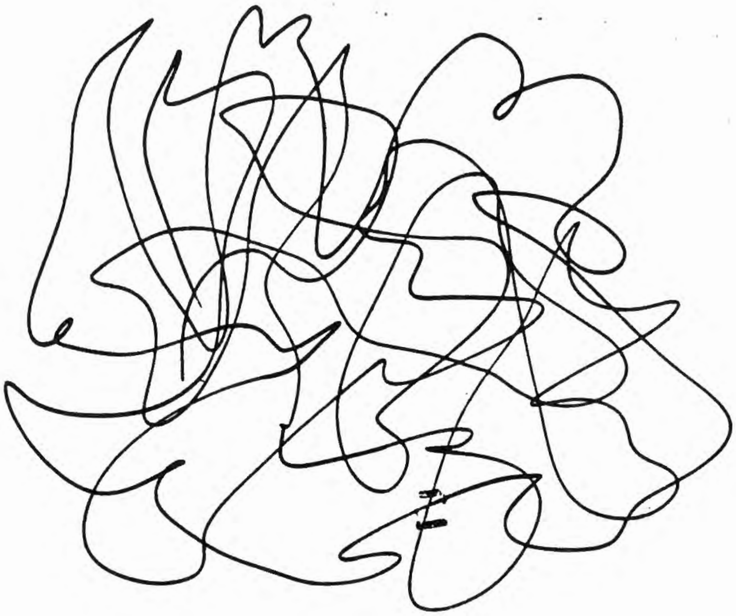
In our view: viscosity is crucial to initiate
but faster than viscous timescale

Reconnection: active research area e.g.

Siggia, Pumir, Kida, Zabusky, Saffman
Ashurst, Kerr, Meiron, Melander, Orszag,
Shelley, Aref

Timescale σ: core size; Γ: circulation

Takaki & Hussain (85)	$\sigma^2/\Gamma = \frac{\sigma^2}{\nu} \cdot \frac{\nu}{\Gamma}$
Schatzle (87)	$\sigma/(s\nu)^{1/2}$, $\sigma^2/(\Gamma\nu)^{1/2}$
Saffman & Leonard (87)	$\frac{1}{2s} \log \frac{\sigma^2 s}{\nu}$
Meiron et al. (88)	$\frac{1}{2s} \log \Gamma/\nu$
Melander & Zabusky (89)	$\log \Gamma/\nu$

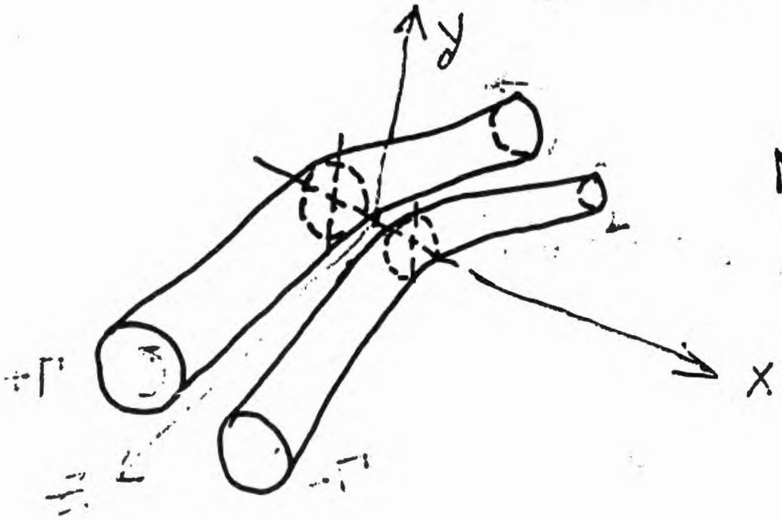


Turb. is
a tangle of
vortices

Reconnection occurs
continuously

Reconnection a
fundamental mech.
self-similarity : Universality

Siggia (1985)
showed filaments
become locally
anti-parallel



Melander & Hussain (88

128^3 spectral, DNS

Compact [illegible]

initial [illegible]

[illegible]

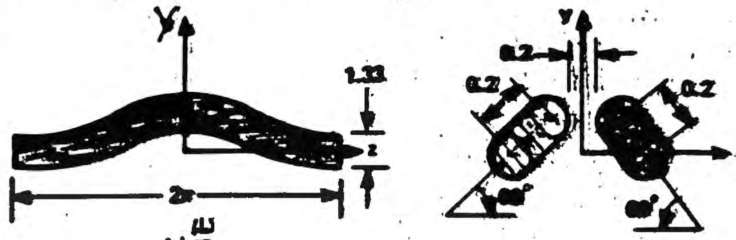
dealiased

[illegible]

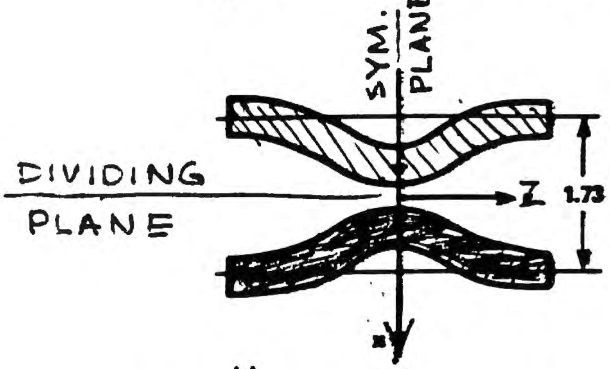
64^3 Spectral, dealiased, $\frac{2}{3}$ truncation in k-space

$\Gamma/\nu = 1000$

Sc = 1



Symmetric



(a)

Sinusoidal perturb. to induce collision

To localize crosslinking

Initial vorticity is Compact Gaussian

$\omega(r) = 0 \quad r > 0.67 r_0$

$\omega(r)$ readjusted to satisfy $\nabla \cdot \vec{\omega} = 0$

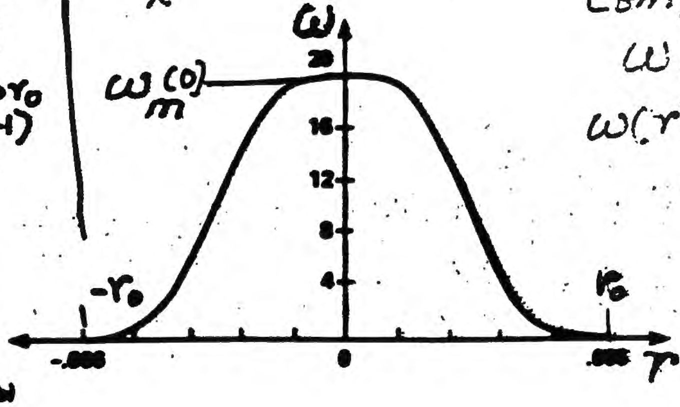
$\omega(r) = 1 - f\left(\frac{r}{r_0}\right)$

$= 0 \quad r > r_0$

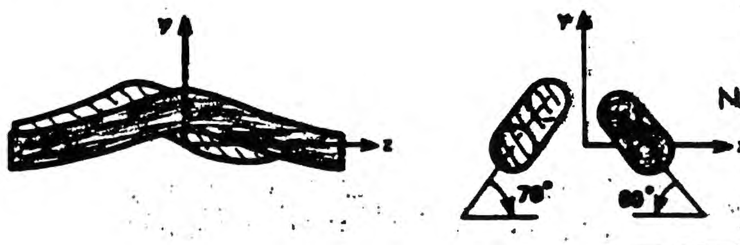
$f(\eta) = e^{-\frac{K}{\eta}} e^{1/(\eta - 1)}$

$K = \frac{e^2}{2} \log 2$

X



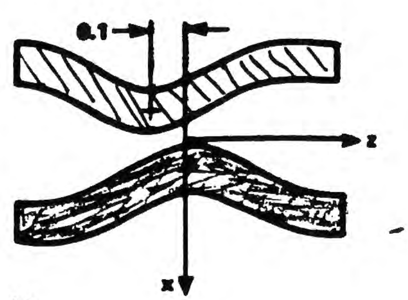
(b)



Asymmetric

No explosive instab.

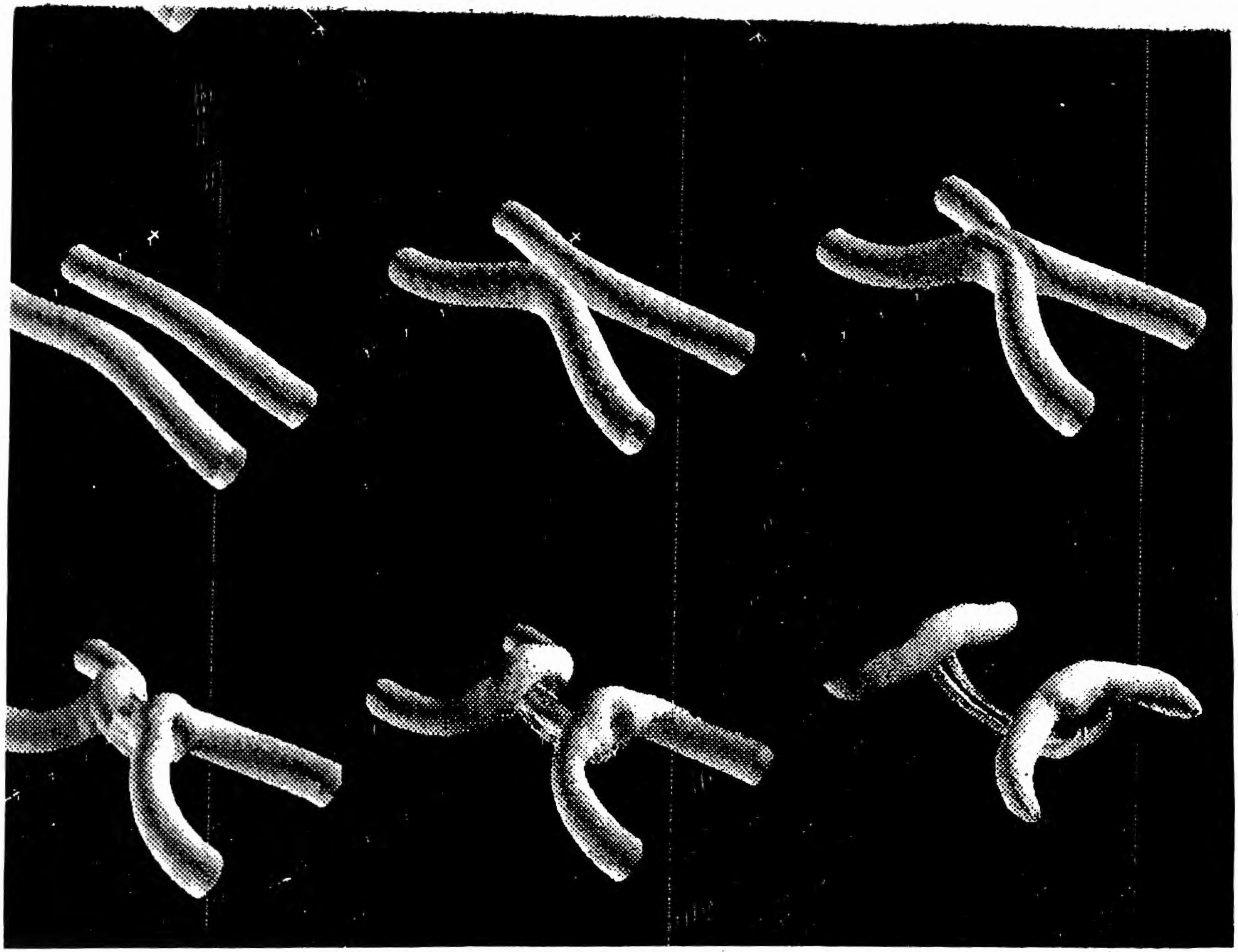
Mention only diff.



(c)

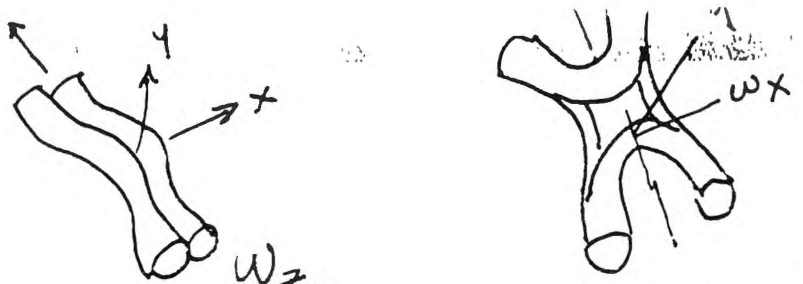
Discuss results at n-d times $t \equiv t^* \omega_m^{(0)}$

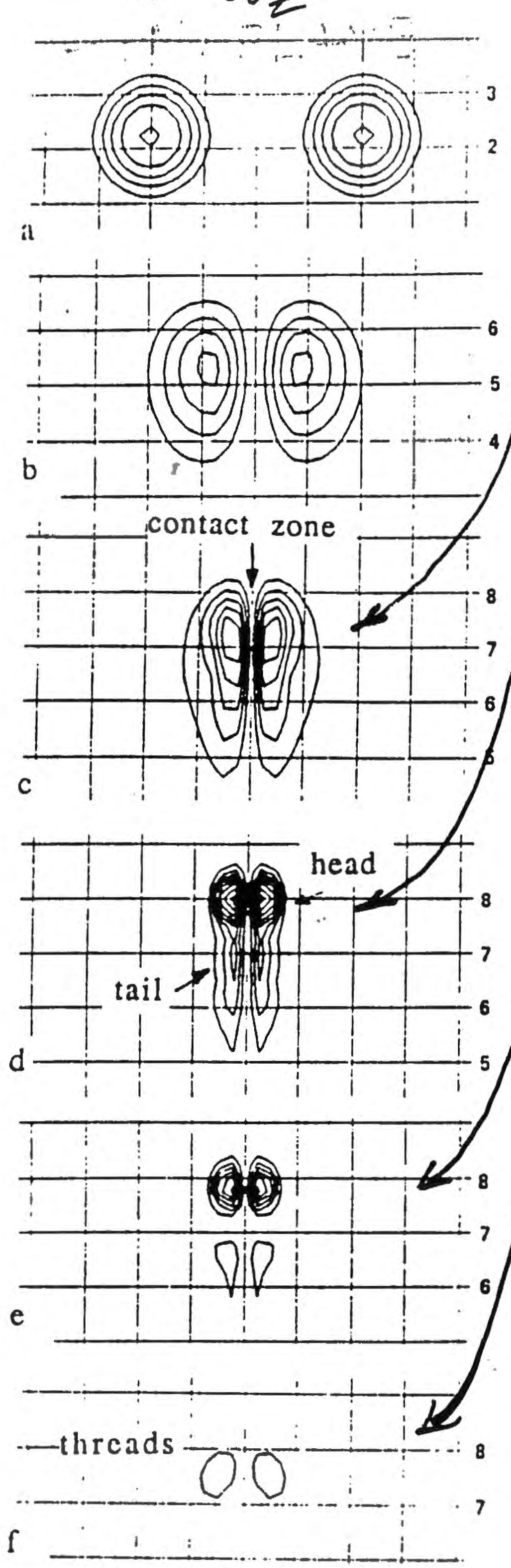
$t = 0, 2, 3, 3.75,$ 4.5 and 6



t=
0
2
3
3.75
4.5
6

$t = t^{*}(\omega) \cdot h_0$ @ 0, 2, 3, 3.75, 4.5, 6; $\frac{\Gamma}{\nu} = 1000$





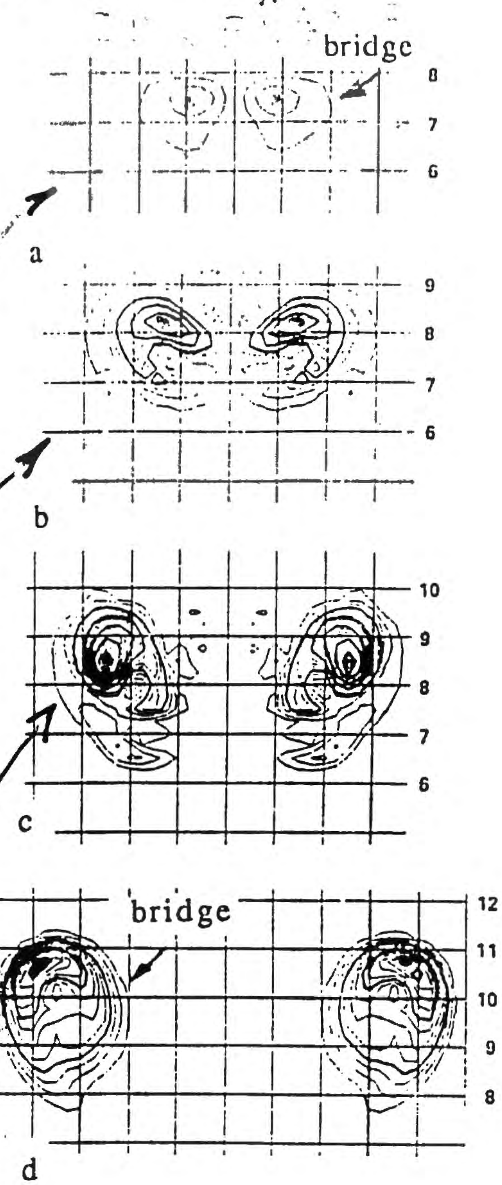


Figure 4. |ω| contours in π_d ; contour increments $\Delta\omega=4$.
(a) t=3.0; (b) t=3.75; (c) t=4.5; (d) t=6.0

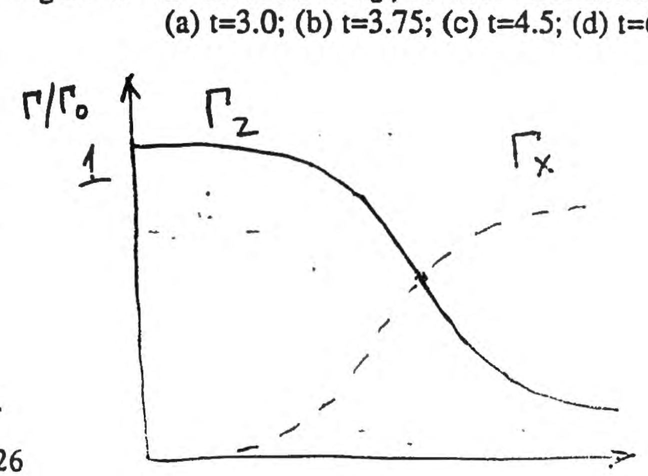
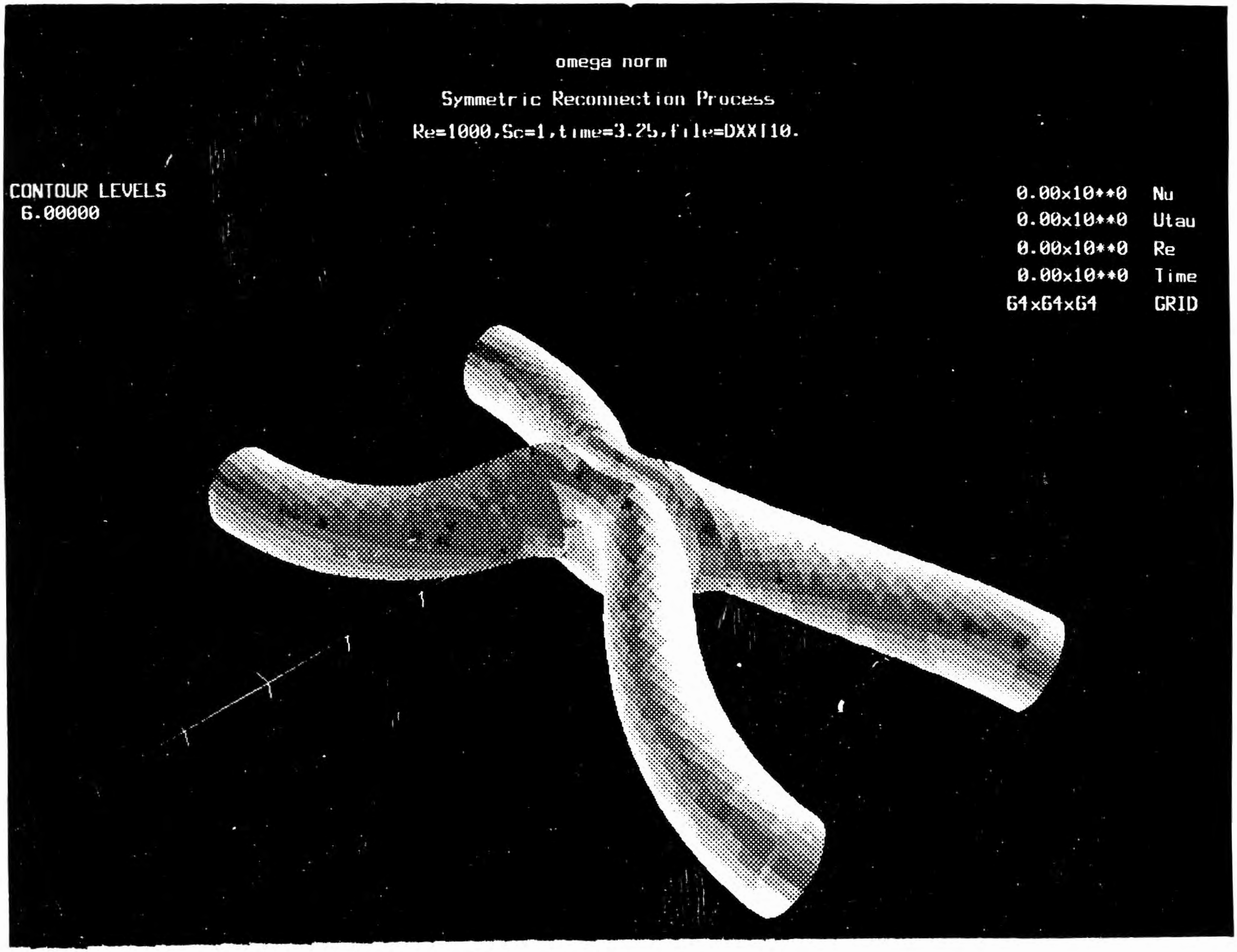


Figure 3. |ω| contours in π_s ; contour increments $\Delta\omega=4$.
(a) t=0; (b) t=2.0; (c) t=3.0; (d) t=3.75;
(e) z=4.5; (f) t=6.0

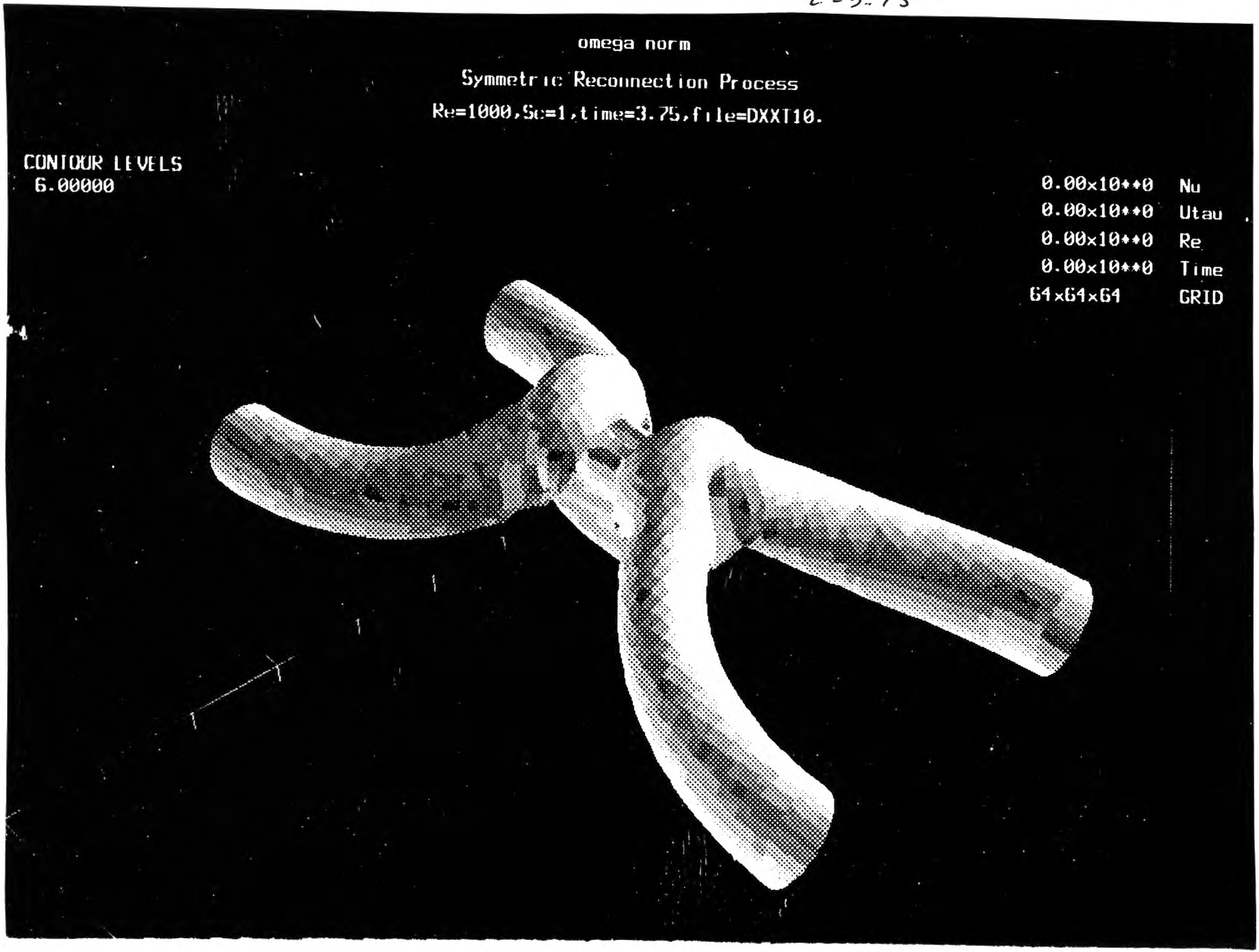
'Bridging' Mechanism

→ the heart of reconnection

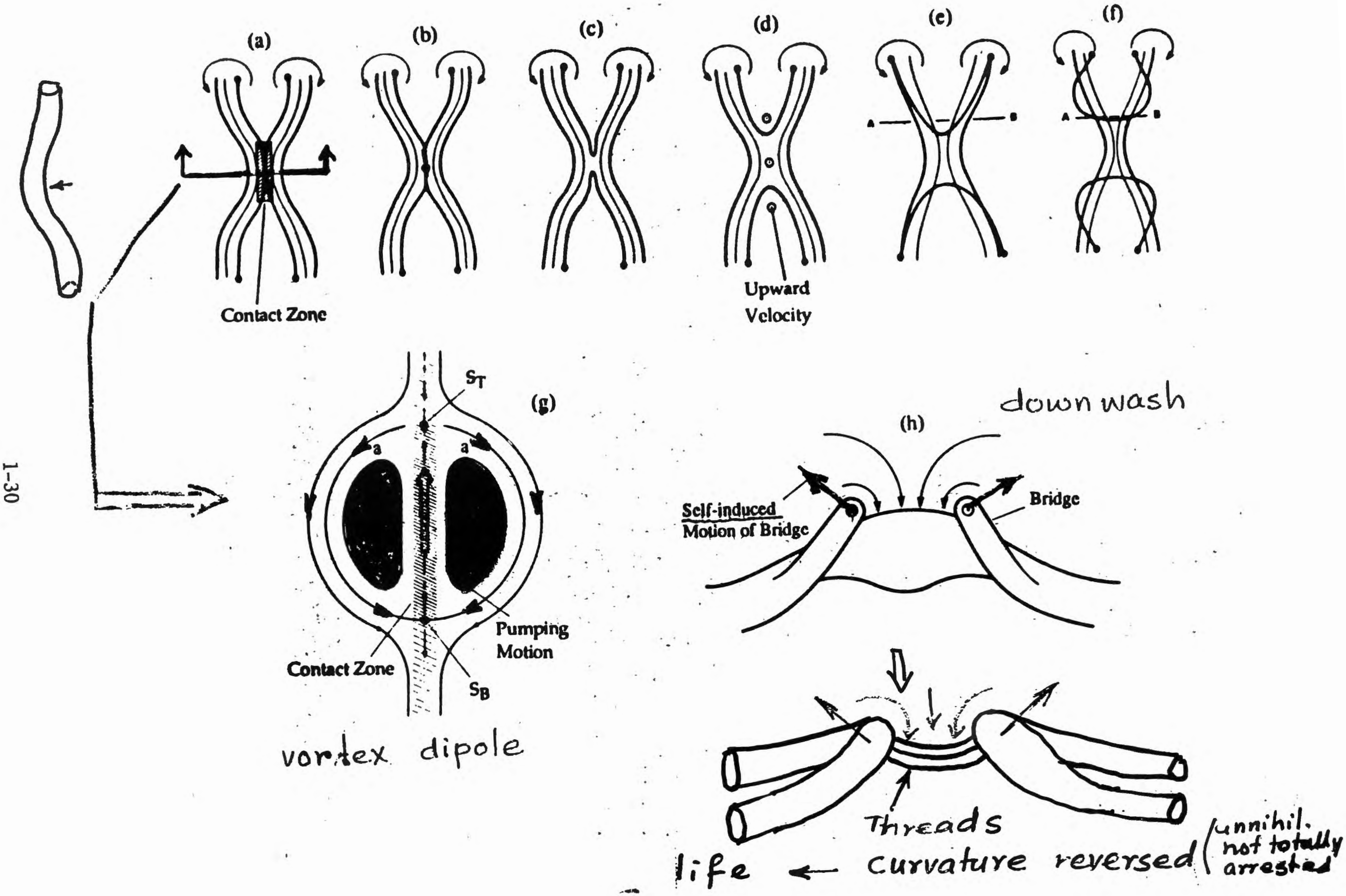
$\tau = 3.25$

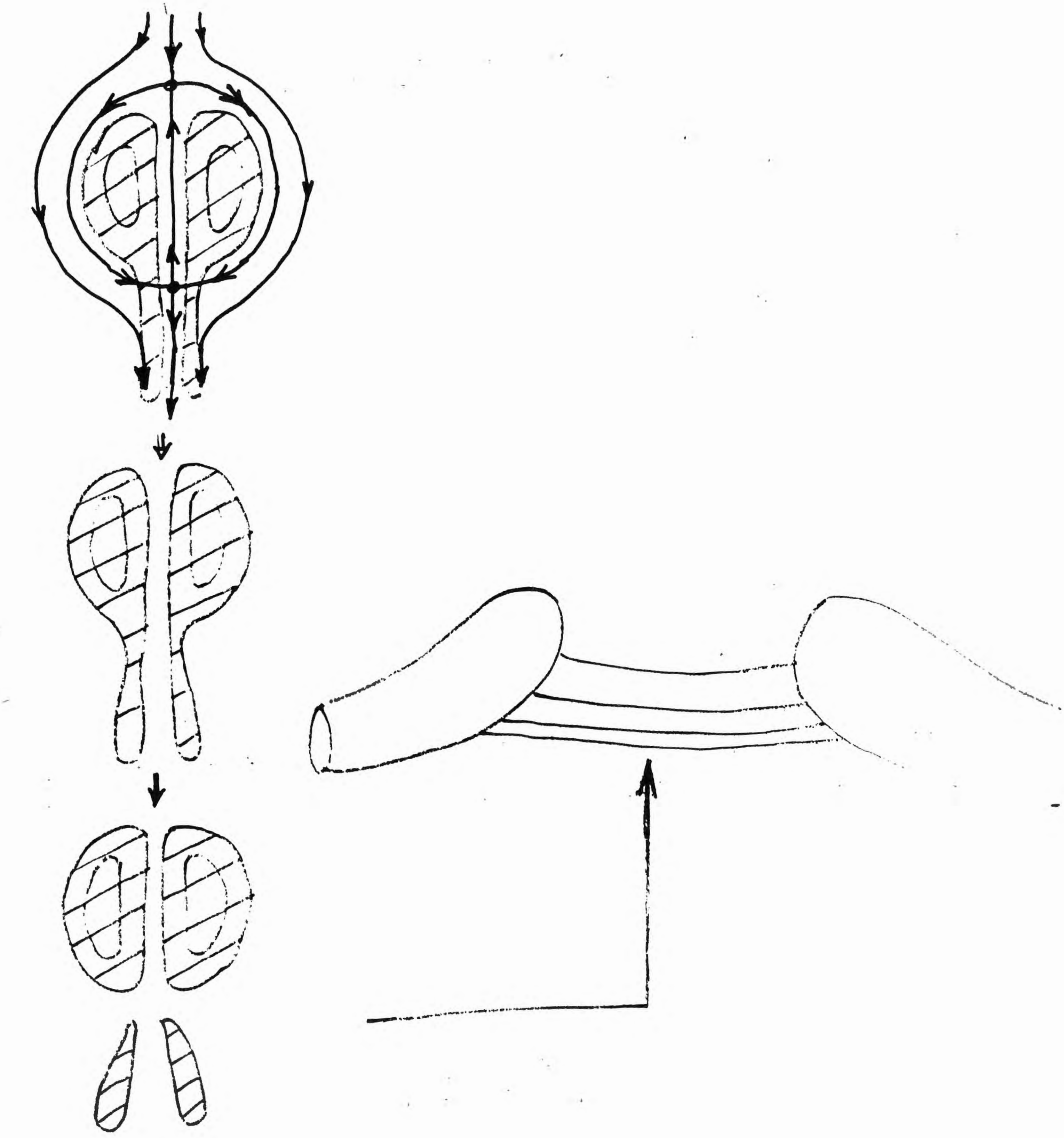

omega norm
Symmetric Reconnection Process
Re=1000,Sc=1,time=3.25,file=DXXI10.
CONTOUR LEVELS
6.00000
0.00x10**0 Nu
0.00x10**0 Utau
0.00x10**0 Re
0.00x10**0 Time
64x64x64 GRID

$t = 3.75$

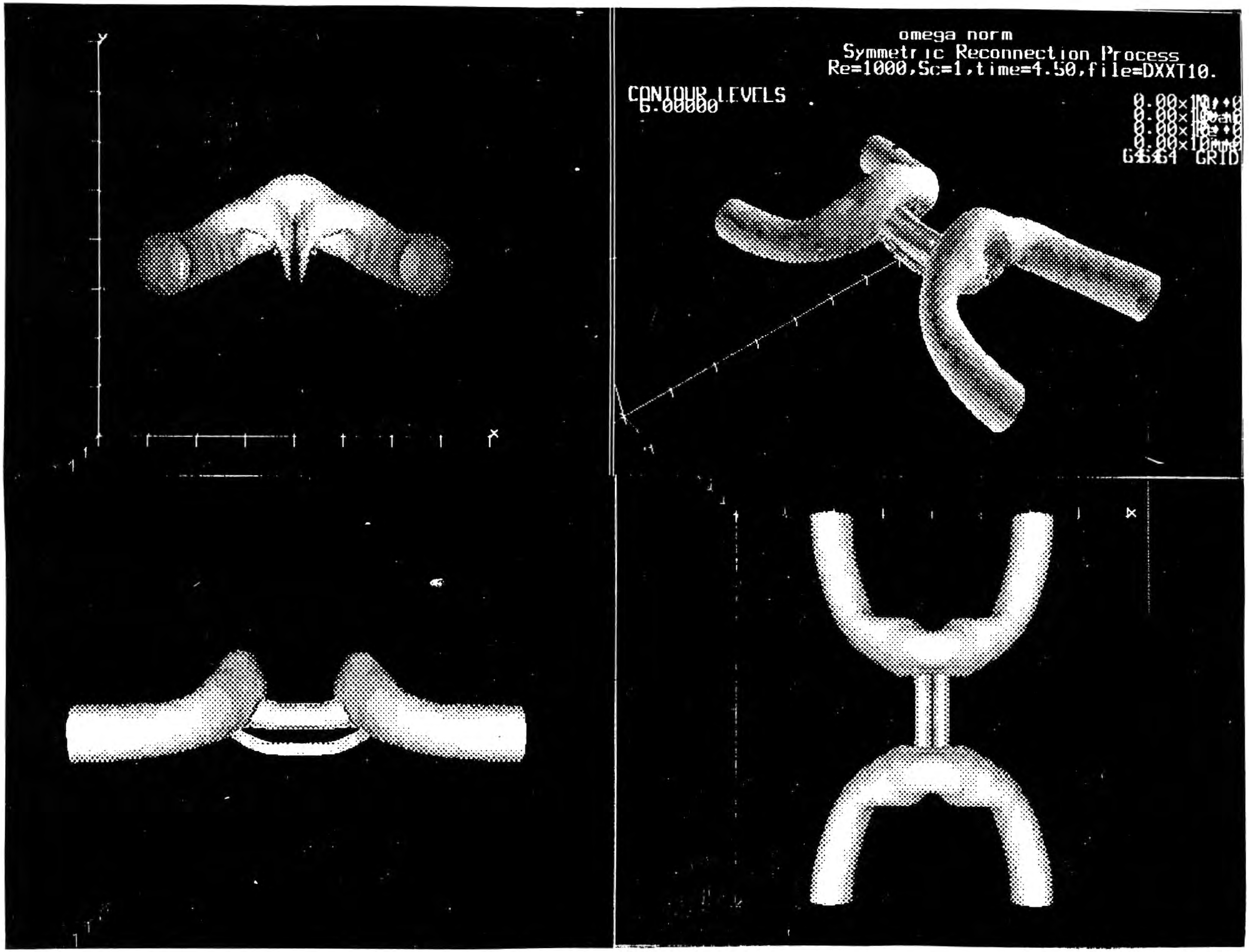


omega norm
Symmetric Reconnection Process
Re=1000,Sc=1,time=3.75,file=DXXT10.
CONTOUR LEVELS
6.00000
0.00x10**0 Nu
0.00x10**0 Utau
0.00x10**0 Re
0.00x10**0 Time
64x64x64 GRID


(a)
(b)
(c)
(d)
(e)
(f)
Contact Zone
Upward Velocity
A
B
S$_T$
(g)
a
a
Pumping Motion
Contact Zone
S$_B$
vortex dipole
down wash
(h)
Self-induced Motion of Bridge
Bridge
Threads
life ← curvature reversed
unnihil. not totally arrested



t=4.5


omega norm
Symmetric Reconnection Process
Re=1000,Sc=1,time=4.50,file=DXXT10.
CONTOUR LEVELS
6.00000
GRID

New Cascade mechanisms (also mixing)

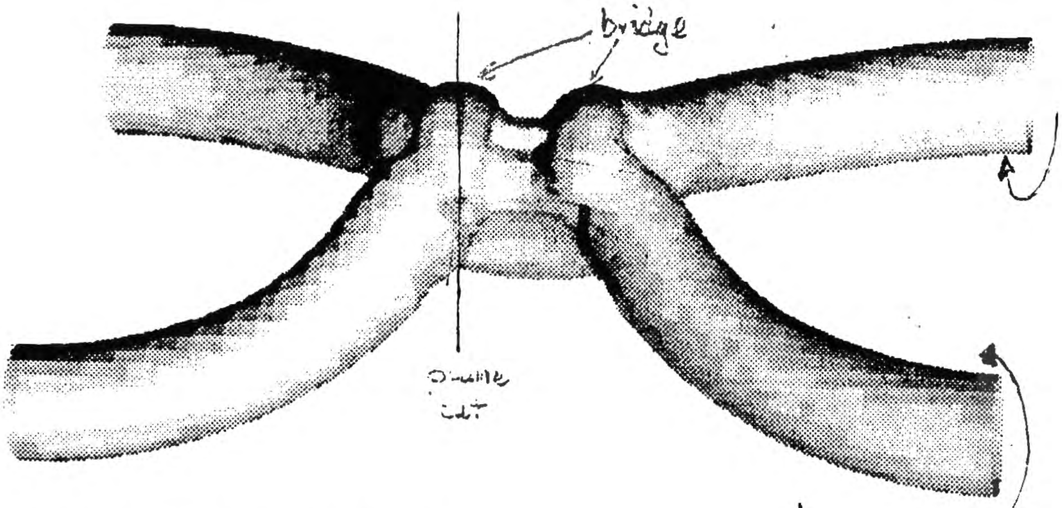
1. Threading
2. Head-tail formation
3. Separation of head from tail
4. Successive reconnection

(in addition to tearing & filamentation)

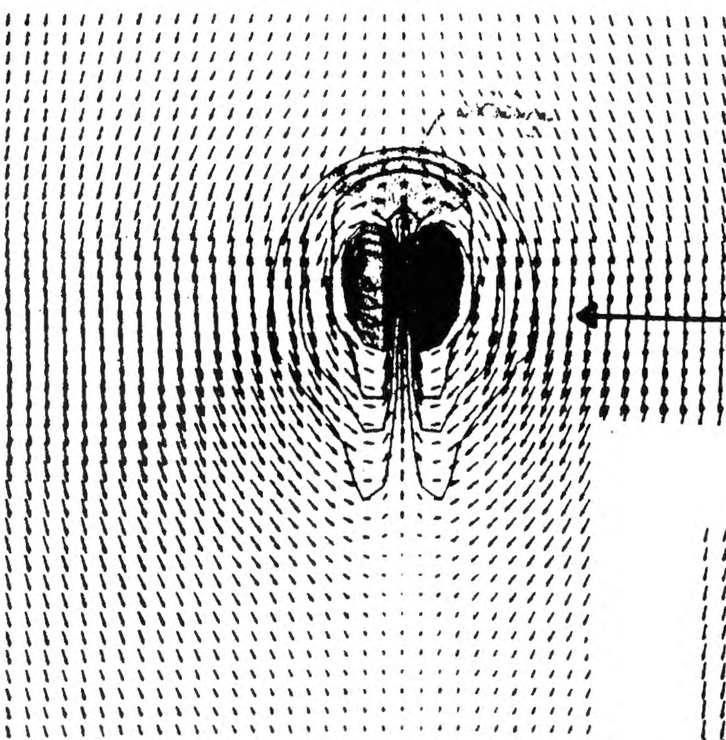
Threading unavoidable because

⇒ curvature reversal by "downwash" overpowering weakened dipole, more weakened by head-tail formation and separation

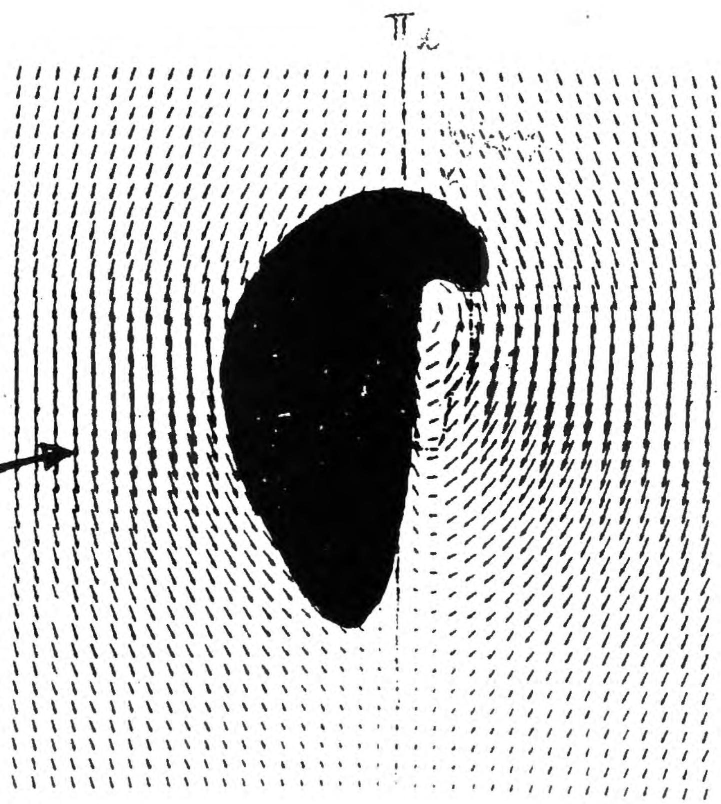
$t=3.5$ $T_s \simeq T_d$ half way through the reconnection



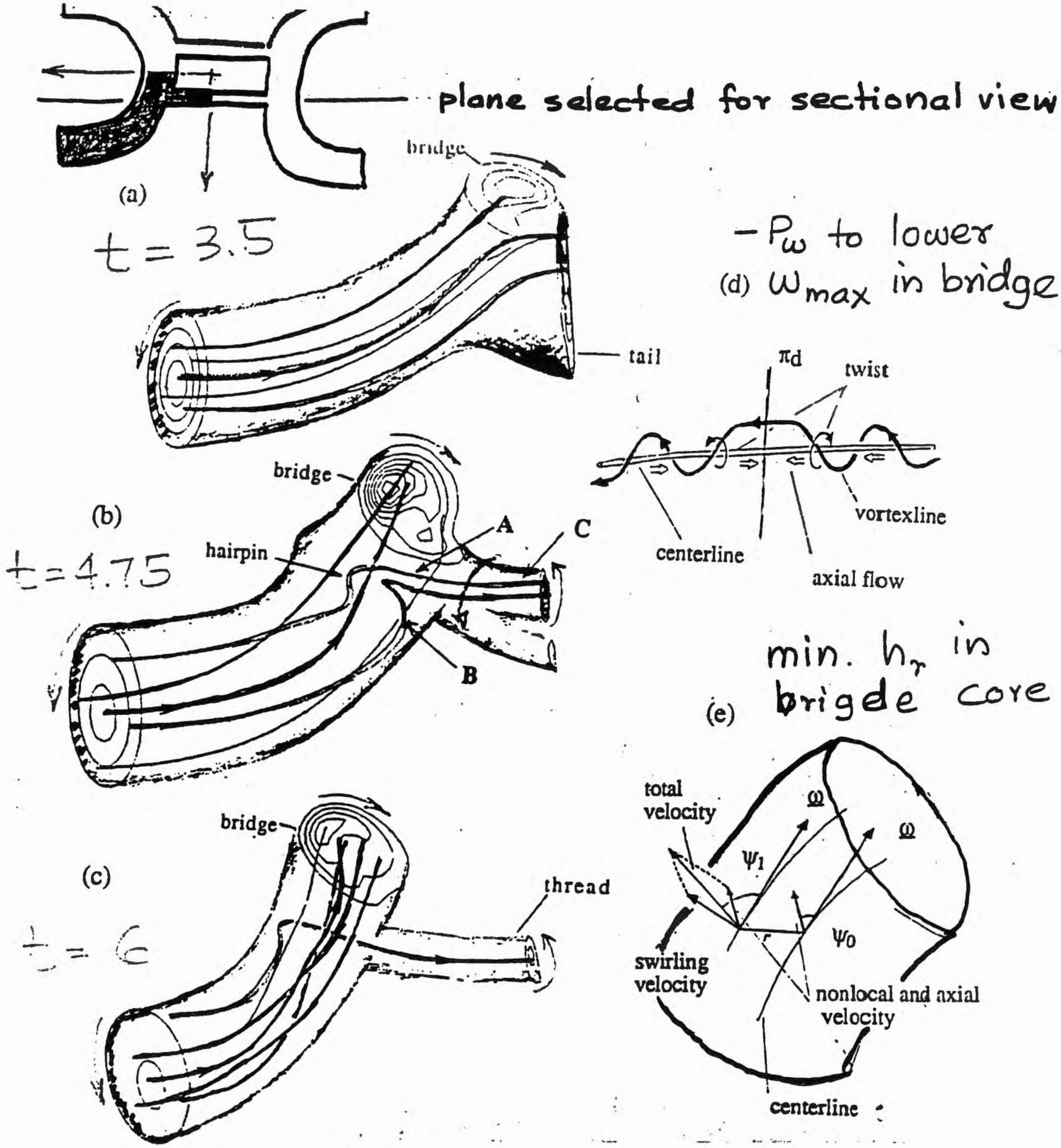
recirculation bubble



vorticity magnitude



passive scalar



Skewed ω distrib. in bridge

Twist $\leftarrow$ pumps fluid to π_d

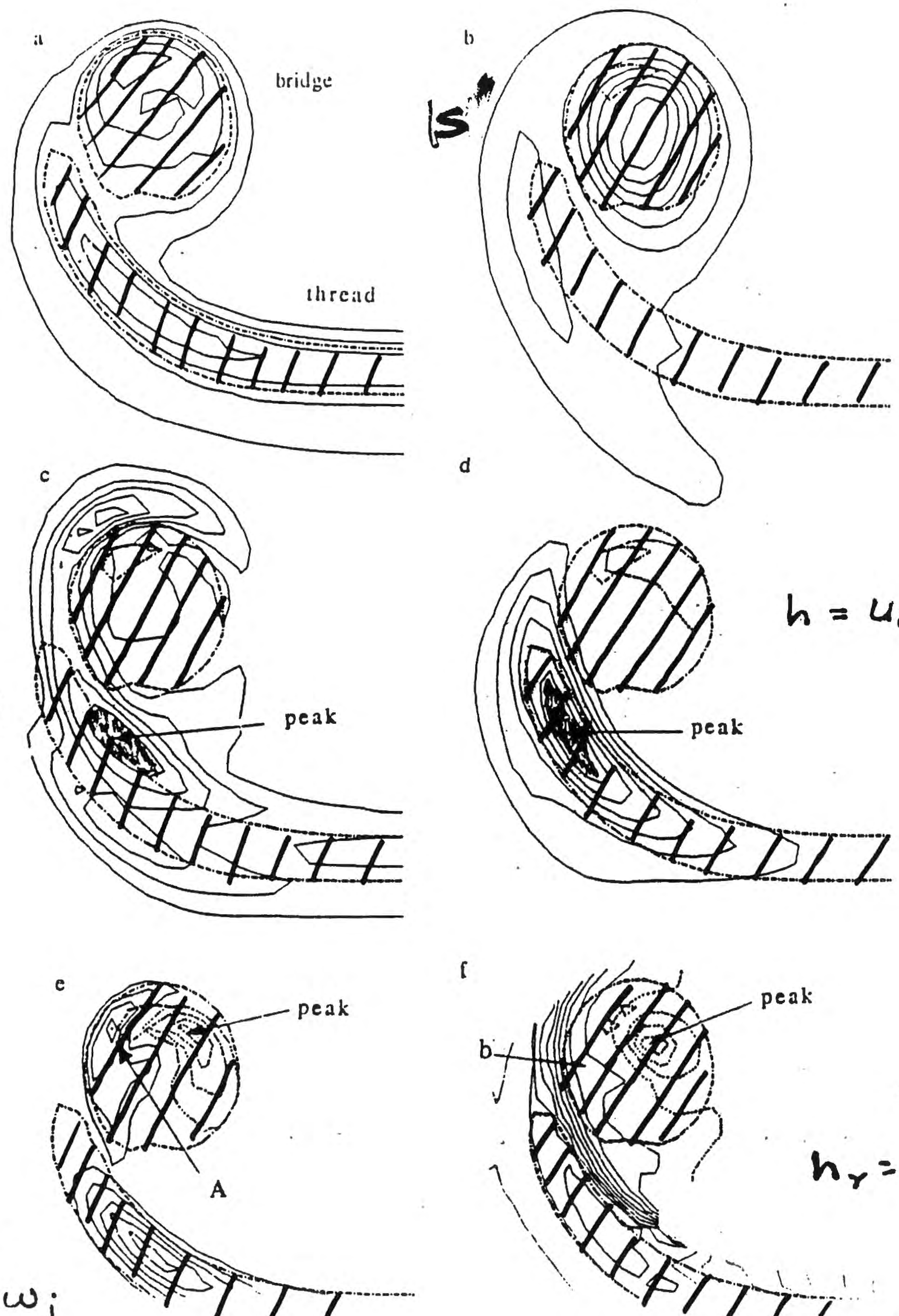
$\rightarrow -P_\omega$

Decreases peak ω (9e, 10e)

" twist vel.

Showing A induces $u \parallel \omega$ in bridge

$t = 6$



$|\omega|$

S

$\epsilon = 2\nu s_{ij} s_{ij}$

$h = u_i \omega_i$

$P_\omega = \omega_i s_{ij} \omega_j$

$h_r = \frac{u_i \omega_i}{|u||\omega|}$

h_r conditional relative helicity (eliminate noise first)

Figure 10. Plane cross-sections at t=6.0 (see caption from figure 8).

Go back

1) P_ω +ve due to hairpin

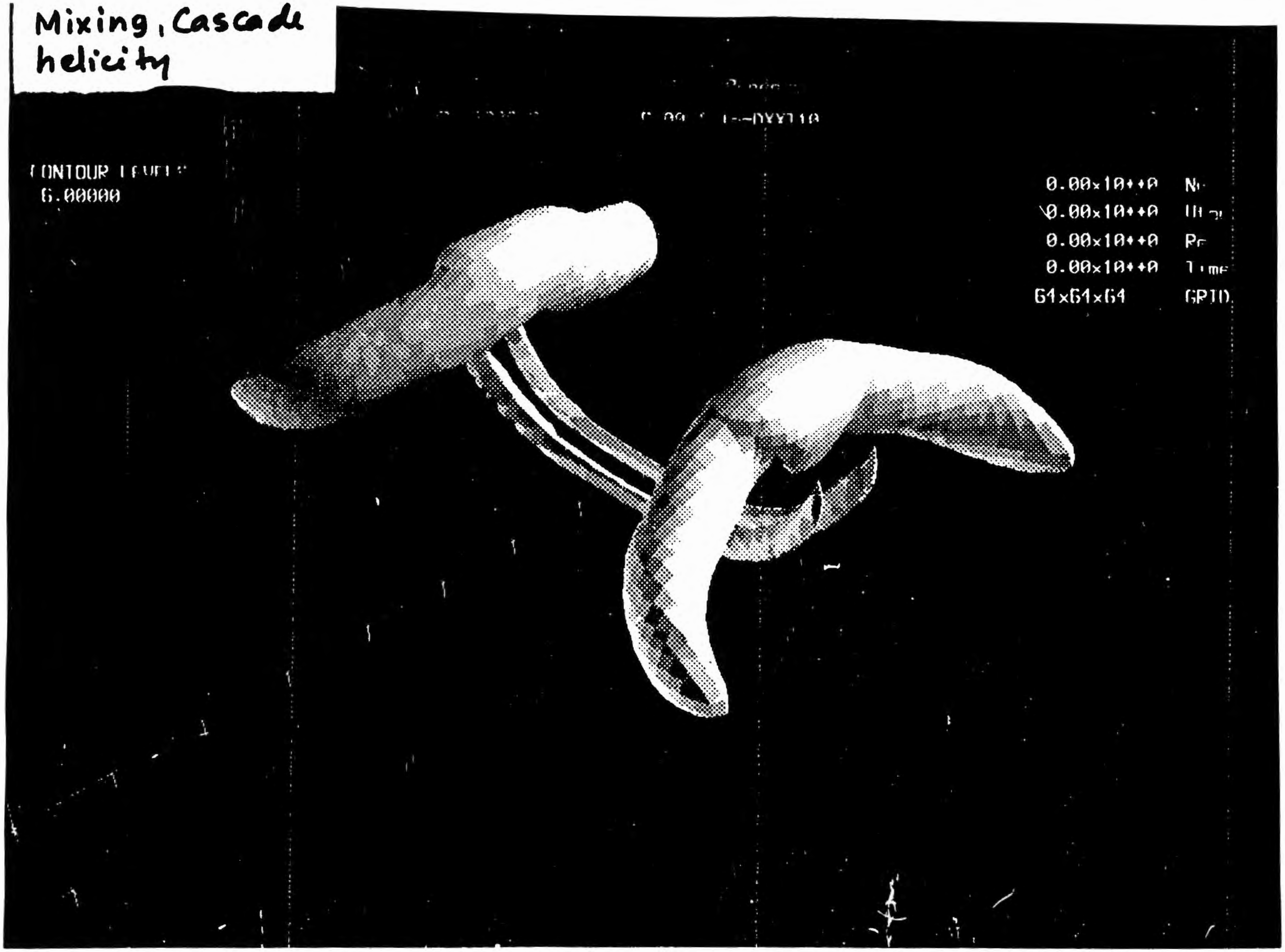
2) Twist → pumping → −ve P_ω.
inviscid vorticity pumping

3) Conditional helicity density
marks center.

4) Marker away from vorticity

5) helicity and dissipation ← no connection

Mixing, Cascade helicity



reverse -> successive reconnection scenario
-> a new cascade mechanism!

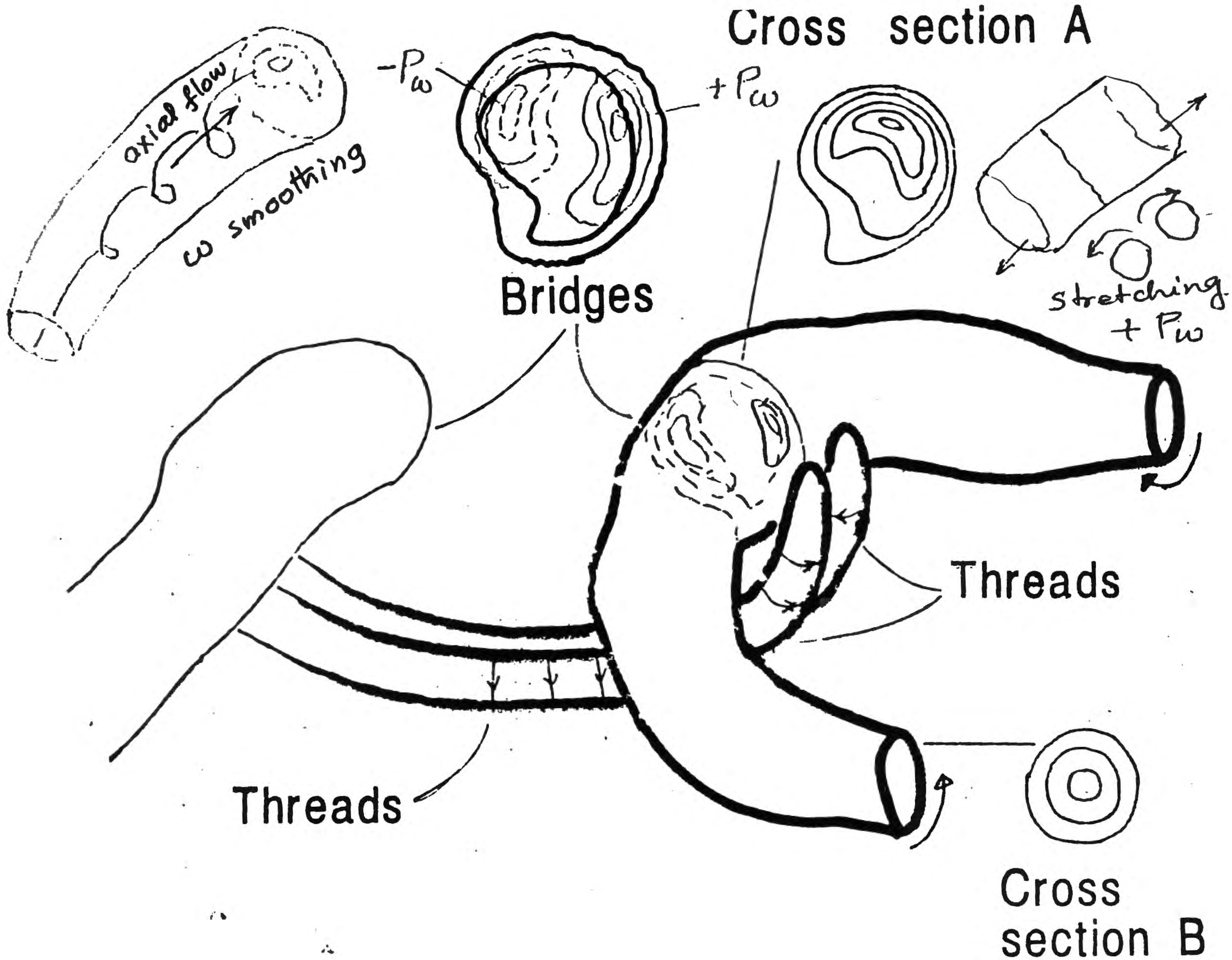
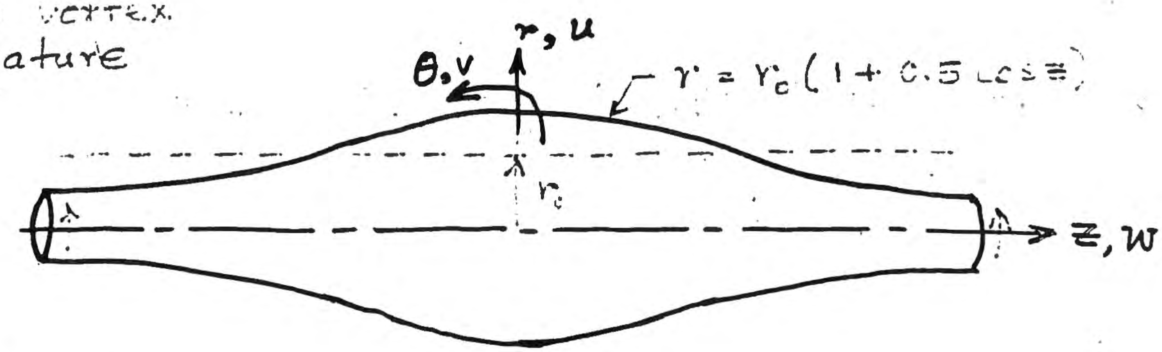

axial flow
ω smoothing
$-P_\omega$
$+P_\omega$
Cross section A
Bridges
stretching
$+P_\omega$
Threads
Threads
Cross section B

Fig. 1

idealized vortex
no curvature



Initial Condition: $\xi = r/r_0 = 1 + 0.5 \cos z$

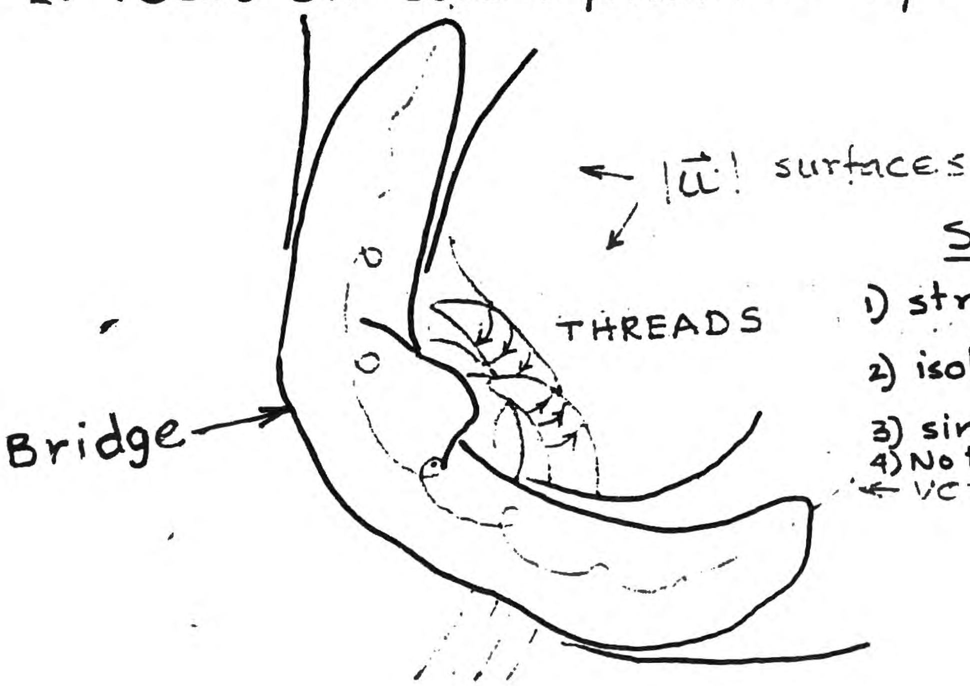
Core: $\omega = \omega_m e^{-4r^2/\xi^2}$

$t = 20/\omega_m(0)$

$Re \equiv \Gamma/\nu \cong \cancel{1}665$ (both lam. & turb.)

Motivations:

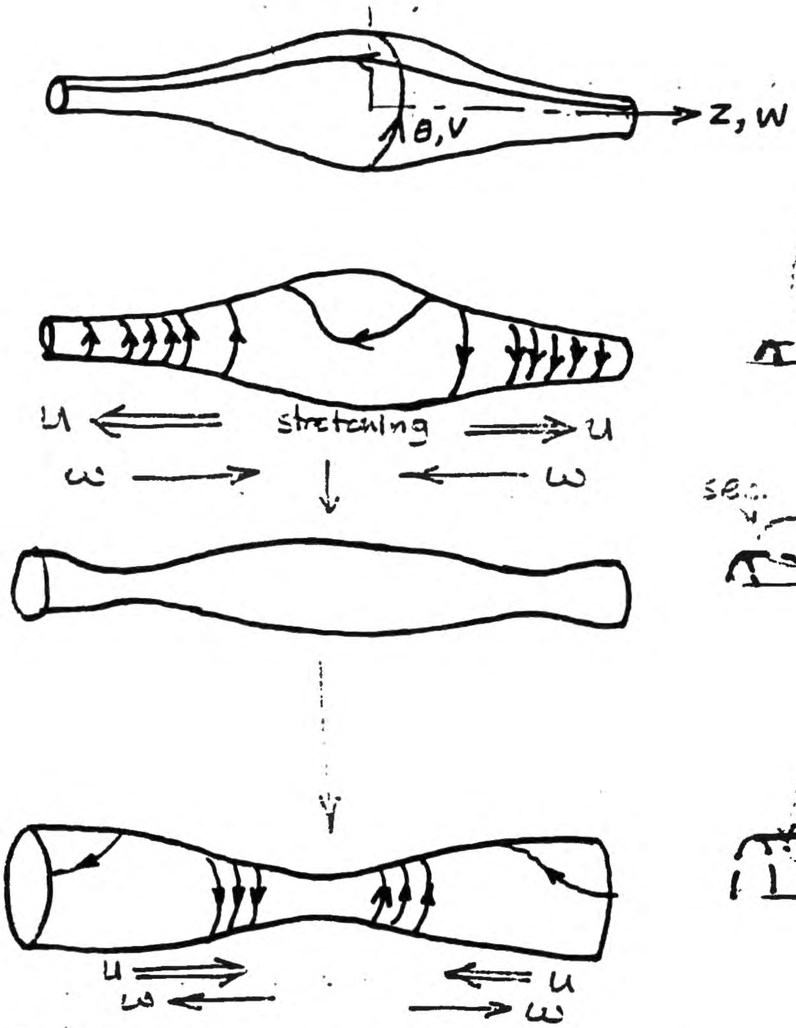
1. Nonuniform cores produced in reconnection: the bridges.
   become uniform faster than diffusion
   mechanism: helical waves & axial flow.
2. Focus on core dynamics by axial flow.

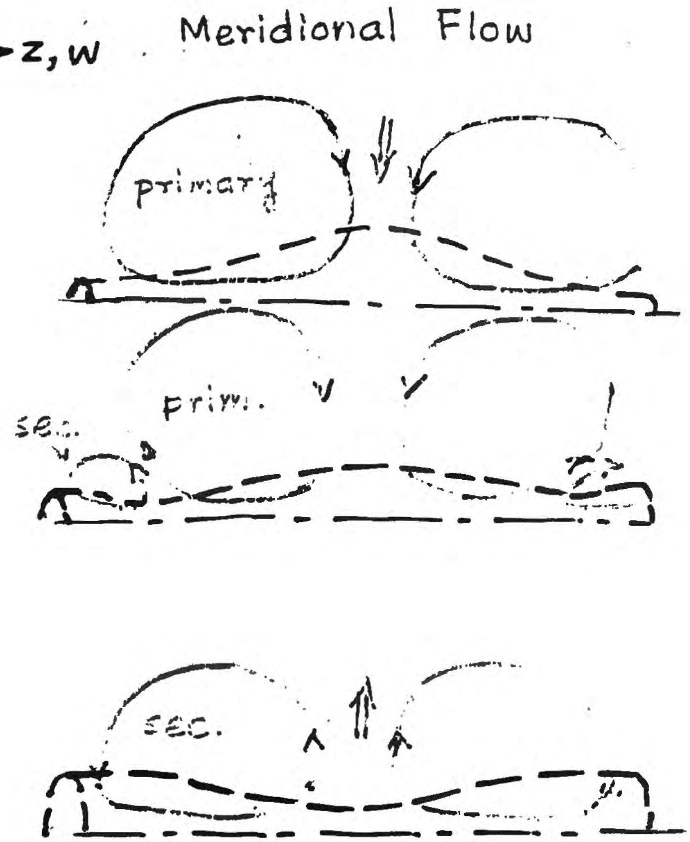


Simplify

1) straight vortex
2) isolated vortex
3) sinusoidal core
4) No thread stretching

← vortex line





$$D_t \zeta = \text{viscous term}; \qquad \zeta \equiv rv \quad \leftarrow \boxed{\text{swirl}}$$

$$D_t \eta = \boxed{\frac{1}{r^4}\frac{\partial(\zeta^2)}{\partial z}} + \text{viscous term}; \qquad \eta \equiv \frac{\omega_\theta}{r} \quad \leftarrow \boxed{\text{meridional flow}}$$

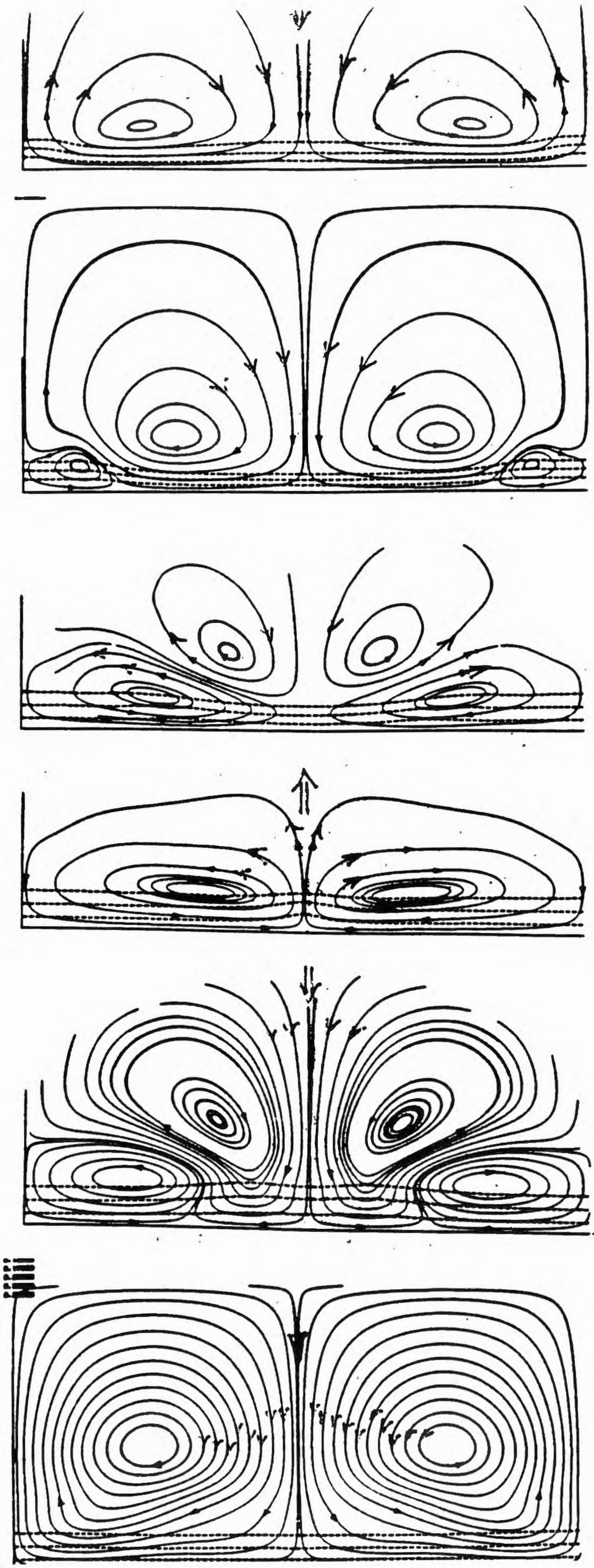
$$D_t = \partial_t + u\partial_r + w\partial_z \quad \text{deriv. in meridional flow}$$

$$\text{meridional flow:} \quad u = \Psi_z/r, \quad v = -\Psi_r/z$$

$$r\omega_\theta = \Psi_{rr} - \Psi_r/r + \Psi_{zz}$$

Azimuthal vorticity, ω_θ, initially zero, is [illegible] by axial [illegible] and [illegible], [illegible] through the coupling [illegible] $\partial\zeta^2/\partial z$. [illegible]

Stream function Ψ
for
meridional flow

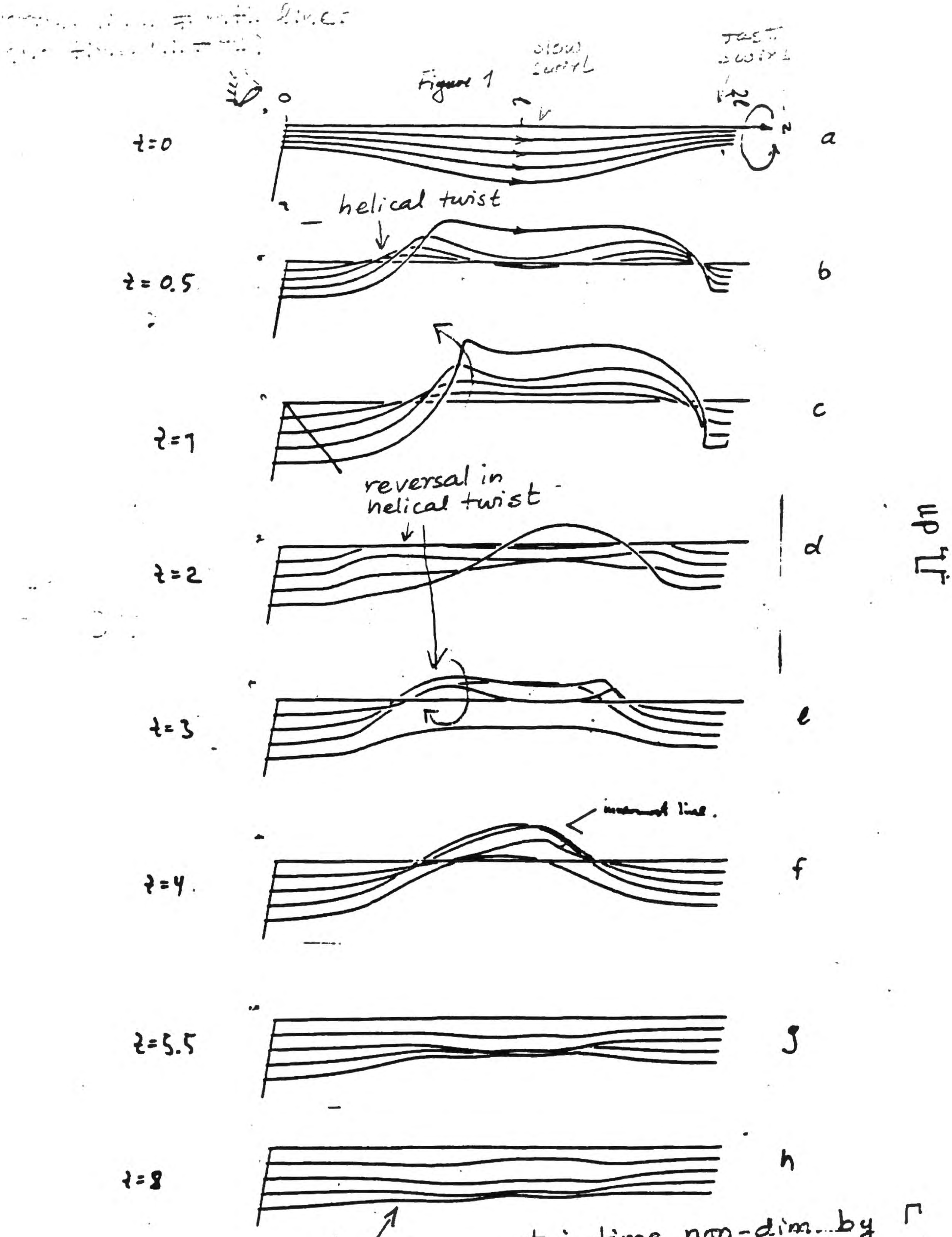


t = 1

t = 2

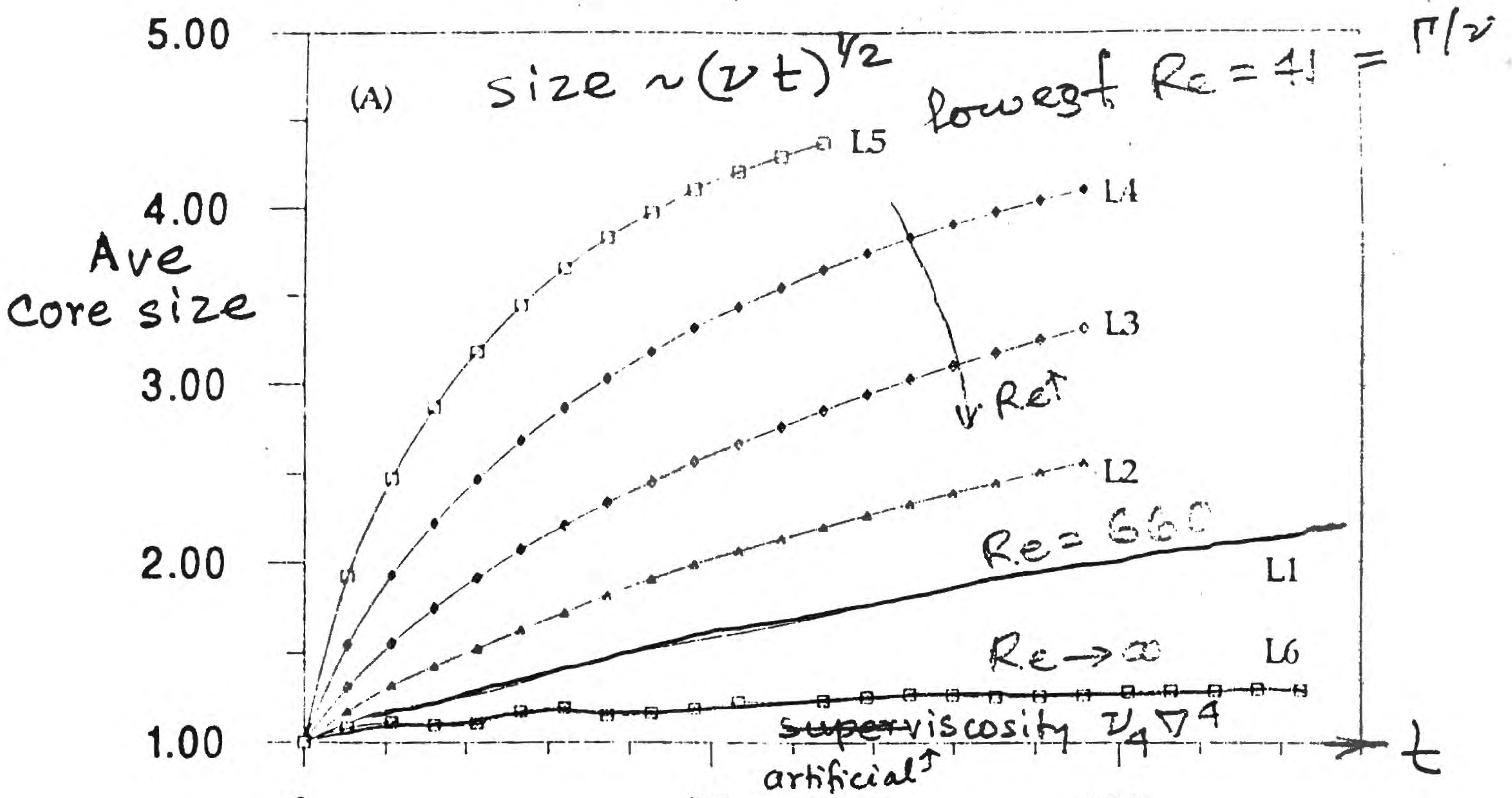
t = 3

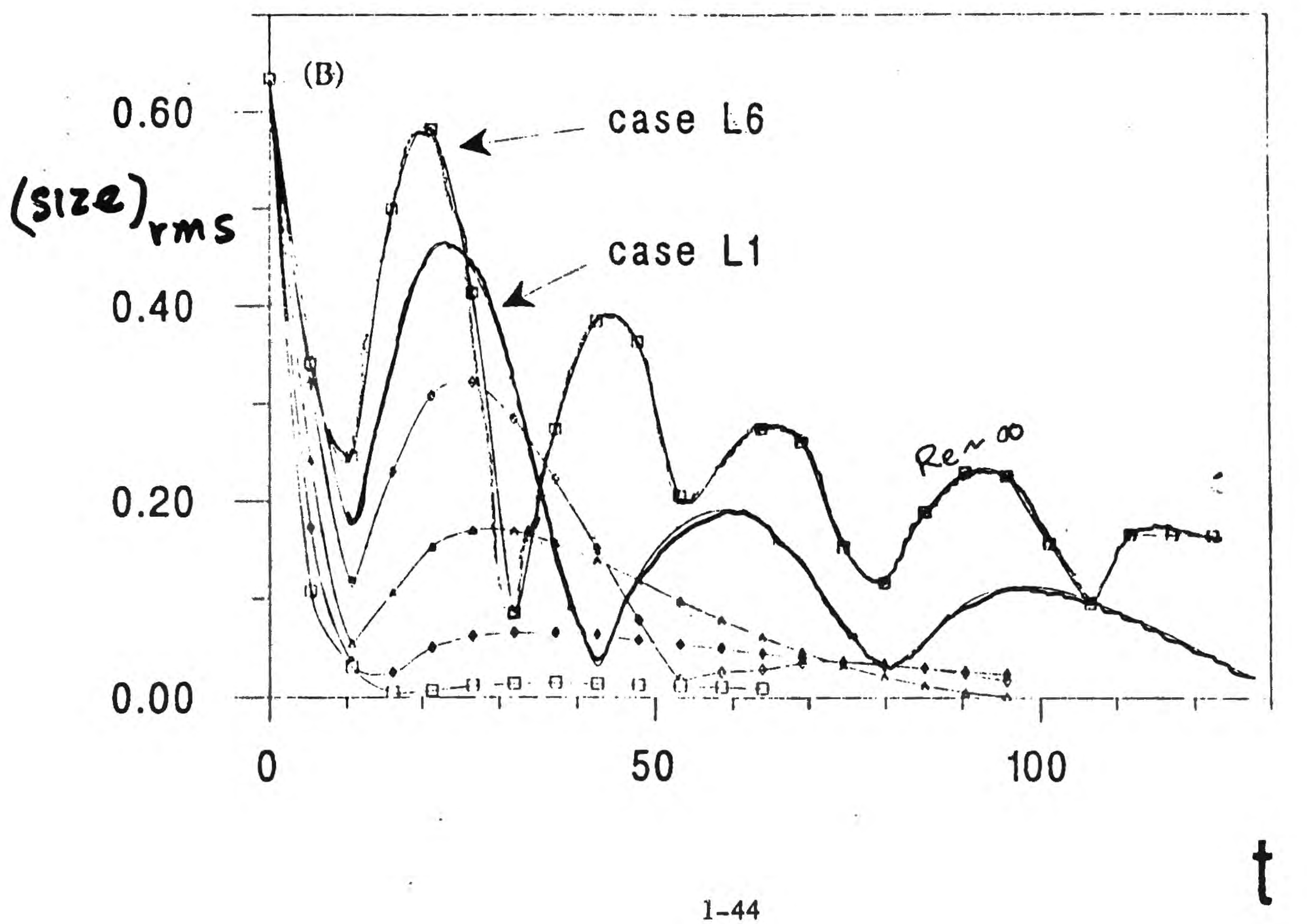
t = 4



almost damped core dyn.

t is time non-dim. by Γ and ang. impulse $\vec{M} = \int_{\mathbb{R}^3} \vec{r} \wedge \vec{V} \, dV$


5.00
4.00
3.00
2.00
1.00
0
50
100
(A)
size ~ (ν t)^1/2
lowest Re = 41 = Γ/ν
Ave Core size
L5
L4
L3
L2
L1
L6
Re↑
Re = 660
Re → ∞
~~super~~viscosity ν4 ∇4
artificial
t


0.60
0.40
0.20
0.00
0
50
100
(B)
(size)rms
case L6
case L1
Re ~ ∞
t

At what rate vortex core σ increase as a result of coupling bet. swirl & meridional and also entrainment?

Defn. of a vortex (controversial subjet)

A kinematic defn. as a spatial connected region with $N_x \equiv [\omega^2 / 2 S_{ij} S_{ij}]^{1/2}$ [illegible]

$\sigma_{uv} \sim (\nu t)^{1/2}$ clearly viscous not inviscid effect

Osc. f inc. with Re but with a finite limit as $Re \to \infty$

Important implication for reconnection common belief recon. in one step

But due to threading, we claim recon. happens in bursts

As $Re \to \infty$, Γ trans. in each burst decreases while duration of each burst finite i.e. $\Gamma_r \to 0$ as $Re \to \infty$

$\Rightarrow$ $t_{rec.} \downarrow$ as $Re \uparrow$

$t_{rec.} \to$ [illegible] as $Re \to \infty$

Evol. of wavepackets, interactions
& core dynamics

can be explained by classical hydrodyn.

as coupling bet. swirl (ξ) & meridional flow (η)

Core dynamics $\rightarrow$ helicity dynamics

Helicity $\vec{\omega}\cdot\vec{u}$

$$|\vec{\omega}\wedge\vec{u}|^2 = |\vec{\omega}|^2|\vec{u}|^2 - h^2 = |\vec{\omega}|^2|\vec{u}|^2(1-h_r^2)$$

$$\mathbf{h}_r \equiv \frac{\vec{\omega}\cdot\vec{u}}{|\vec{\omega}||\vec{u}|} \qquad h_r\uparrow \;\Rightarrow\; \vec{\omega}\wedge\vec{u}\downarrow$$

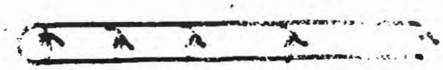
but $\nabla\wedge(\vec{\omega}\wedge\vec{u})$ can be lar

NSE $\qquad \vec{u}_t + \vec{\omega}\wedge\vec{u} = -\nabla\left(\frac{p}{\rho}+\frac{u^2}{2}\right) + \nu\Delta\vec{u}$

If Lamb vector $\omega\wedge u$ not solenoidal (i.e. only potential)

$$\Rightarrow \quad \vec{\omega}_t = \nu\Delta\vec{\omega} \qquad \text{NO CASCADE}$$

Thus $h_r = \pm 1$ (Beltramization) sufficient, not necessary for cascade suppression

Example: rectilinear vortex 
no axial flow.
$\vec{\omega}\wedge\vec{u}$ large but purely potential

h, h_r, not being Galilean invariant (Speziale?),
is not a useful quantity in turbulence
(Rogers & Moin).

Alternative approach: Helical Wave Decomposition
Moses (71), Lesieur (86)

Lamb vector $|\omega \wedge u|^2 = \omega^2 u^2 (1 - h_r)$

$\omega \wedge u$ is the NL term and responsible for cascade (i.e. trans. to ss)

Expect small cascade if $h_r \simeq 1$

If $h_r = 1$, $\omega \wedge u = 0$ sufficient for cascade suppression

If $h_r \neq 1$, then $\omega \wedge u \neq 0$ hence though nonzero, can be potential

still complete cascade suppression.

Hence $h_r = 1$ is sufficient but not necessary.

2.

3. If cascade is suppressed (as in rect. vortex) $\rightarrow$ $h_r \neq \pm 1$ (actually zero)

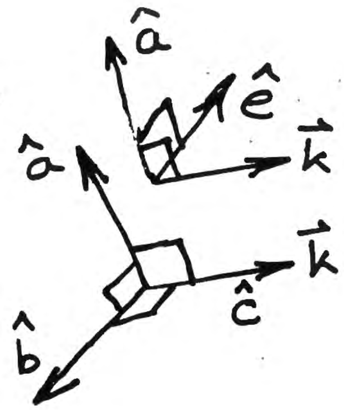
4. In a particular frame, $h_r = 0 \rightarrow$ but $\omega \wedge u$ can be large but purely potential

so vort. eqn. $\rightarrow$ diffusion eqn.

i.e. no cascade

5. Thus $h_r = \pm 1$ (Beltramization) is sufficient, but not necessary.

Complex Helical Wave Decomposition



Let $\hat{e}$ any arbitrary fixed unit vector

For each $\vec{k}$ in Fourier space, introduce

$$\hat{a}(\vec{k}) = \frac{\vec{k}\wedge\hat{e}}{|\vec{k}\wedge\vec{e}|} \; ; \; \hat{b}(\vec{k}) = \frac{\vec{k}\wedge\hat{a}}{|\vec{k}\wedge\hat{a}|} \; ; \; \hat{c}(\vec{k}) = \frac{\vec{k}}{k}$$

$\hat{e}$ only helps introduce orthonormal basis [illegible].

$\Rightarrow$ any vector function $\vec{F}(\vec{x})$ is divergence free if its Fourier coeff. $\vec{F}^f(\vec{k})$ is $\perp \vec{k}$ i.e. $\vec{k}\cdot\vec{F}^f = 0$
i.e. $\vec{F}^f$ must be a linear comb. of $\hat{a}$ & $\hat{b}$.

can show that 'complex helical waves'

$$\vec{V}^+(\vec{k},\vec{x}) = [\hat{b} - i\hat{a}]e^{i\vec{k}\cdot\vec{x}}$$
$$\vec{V}^-(\vec{k},\vec{x}) = [\hat{b} + i\hat{a}]e^{i\vec{k}\cdot\vec{x}}$$

are orthogonal eigenfunctions of curl operator:

$$\nabla\wedge\vec{g} = \lambda\vec{g} \qquad \text{where } \lambda = \pm k$$

Now, velocity $(\vec{u})$ and vorticity $(\vec{\omega})$ can be expressed as sum of right and left handed components: $\vec{V}^+, \vec{V}^-$

$$\vec{u}(\vec{x},t) = \vec{u}_R + \vec{u}_L = \sum_k u^+(\vec{k},t)\vec{V}^+(\vec{k},x) \quad + \sum_k u^-\vec{V}^-$$

$$\vec{\omega}(\vec{x},t) = \vec{\omega}_R + \vec{\omega}_L = \sum_k k u^+\vec{V}^+ \quad + \sum_k k u^-\vec{V}^-$$

corresponds to $+k$ corresponds to $-k$

[illegible]

$$\vec{\omega} = \vec{\omega}_R + \vec{\omega}_L$$

Coupling of $\vec{\omega}_R$ and $\vec{\omega}_L$ better understood using projection operators P^+, P^-

Applying to N-S Eqn: $\frac{\partial \vec{u}}{\partial t} + \vec{\omega} \wedge \vec{u} = -\nabla\left(\frac{p}{\rho} + \frac{u^2}{2}\right) + \nu \Delta \vec{u}$

$$\Rightarrow \quad \frac{\partial \vec{\omega}_R}{\partial t} = -P^+(\nabla \wedge (\vec{\omega} \wedge \vec{u})) + \frac{1}{Re} \Delta \vec{\omega}_R$$

Rewrite for physical interpretation

$$\begin{aligned}
\frac{\partial \vec{\omega}_R}{\partial t} = & -\nabla \wedge (\vec{\omega}_R \wedge \vec{u}_R) \\
& + P^-[\nabla \wedge (\vec{\omega}_R \wedge \vec{u}_R)] \\
& + P^+[(\vec{u}_L \cdot \nabla)\vec{\omega}_R] \\
& + P^+[(\vec{\omega}_R \cdot \nabla)\vec{u}_L] \\
& - P^+[\nabla \wedge (\vec{\omega}_L \wedge \vec{u})] \\
& + \frac{1}{Re} \Delta \vec{\omega}_R
\end{aligned}$$

2nd Terms **1: inviscid self-evol. of $\vec{\omega}_R$**

5th **2: gen. of $\vec{\omega}_L$ by evol. of $\vec{\omega}_R$**

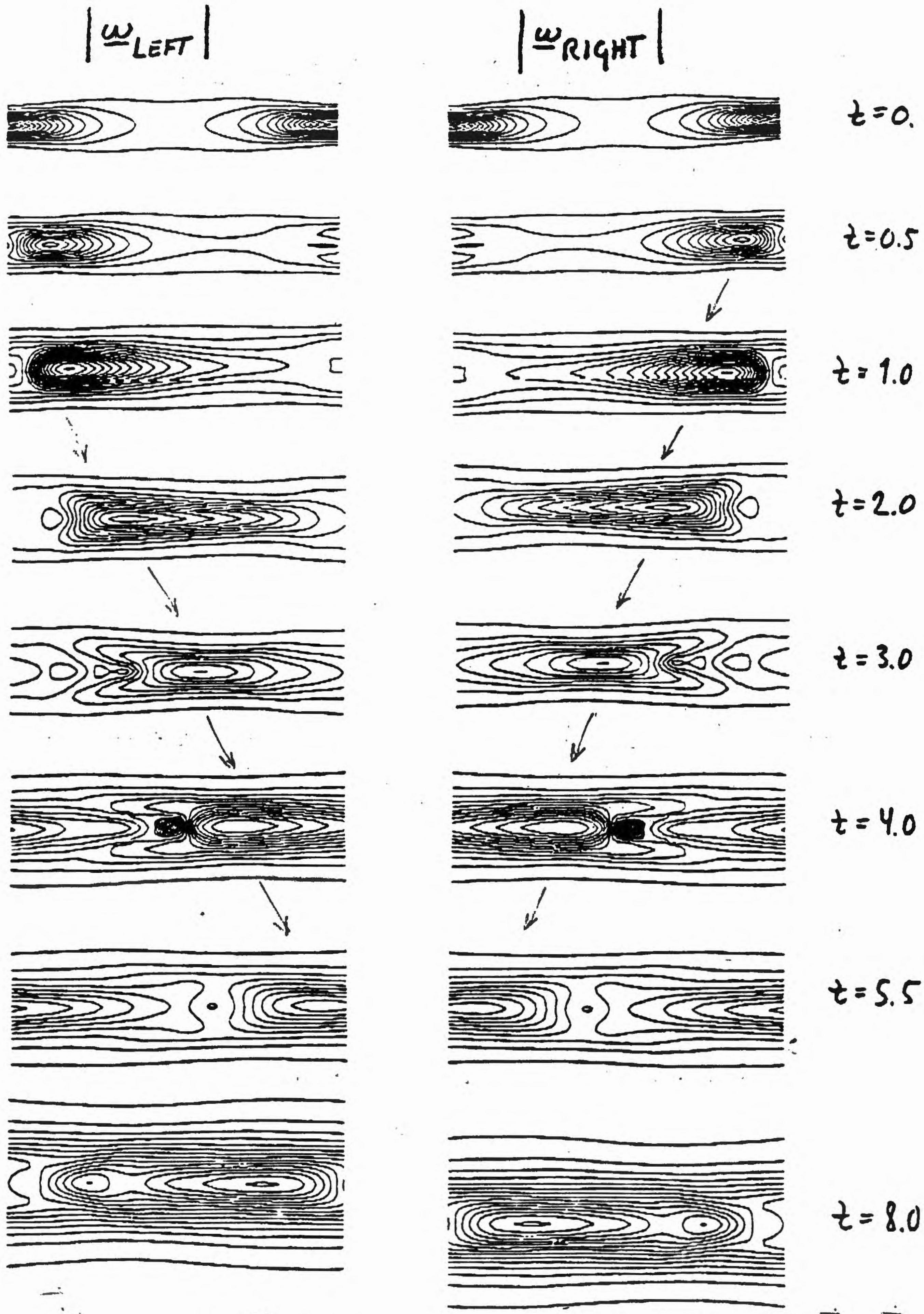
Most dom **3: contrib. to $\vec{\omega}_R$ by its adv. by $\vec{u}_L$**

4th **4: $\vec{\omega}_R$ gen. by its stretching by $\vec{u}_L$**

3rd **5: $\vec{\omega}_R$ growth by evol. of $\vec{\omega}_L$: includes ω_R gen. by evol. ~~by~~ of ω_L + right handed contrib. for stretching and adv. of ω_L by u_R**

6: viscous diff. of ω_R

last Ret


$|\underline{\omega}_{LEFT}|$
$|\underline{\omega}_{RIGHT}|$
$t=0.$
$t=0.5$
$t=1.0$
$t=2.0$
$t=3.0$
$t=4.0$
$t=5.5$
$t=8.0$

initially $\vec{\omega}_R$ only

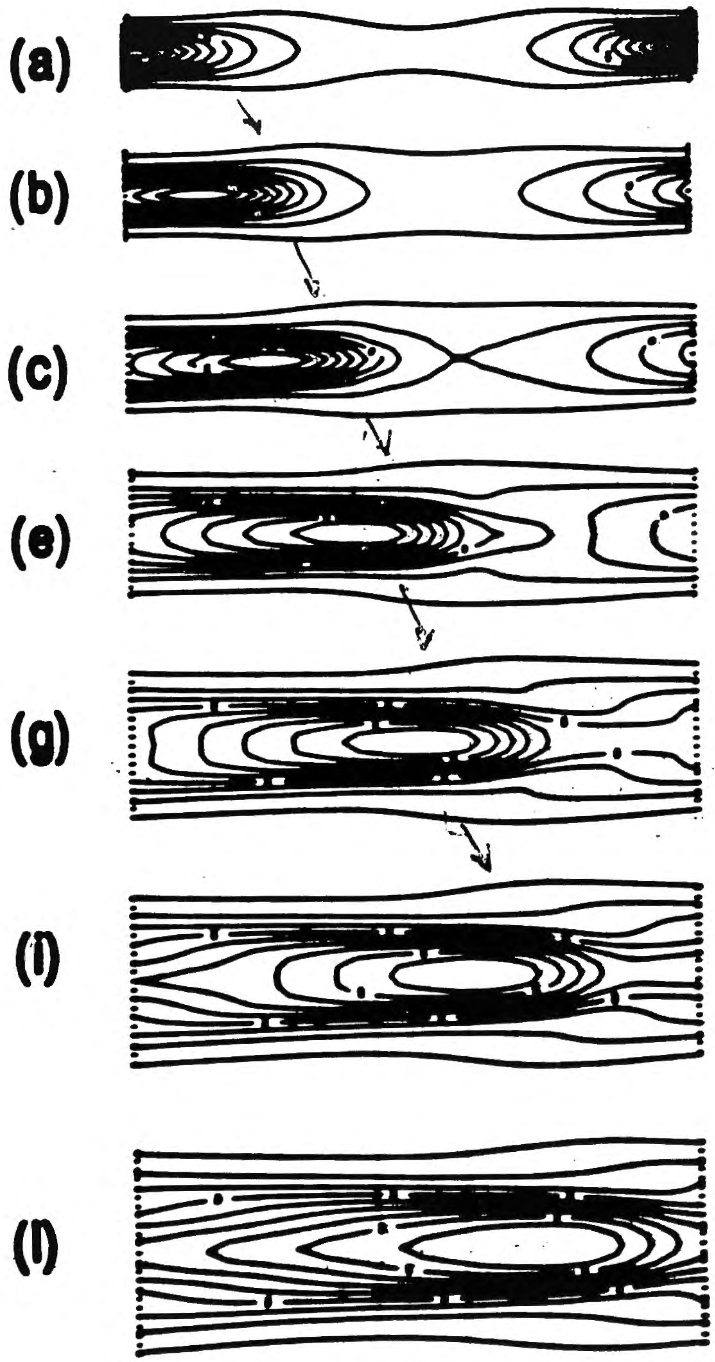
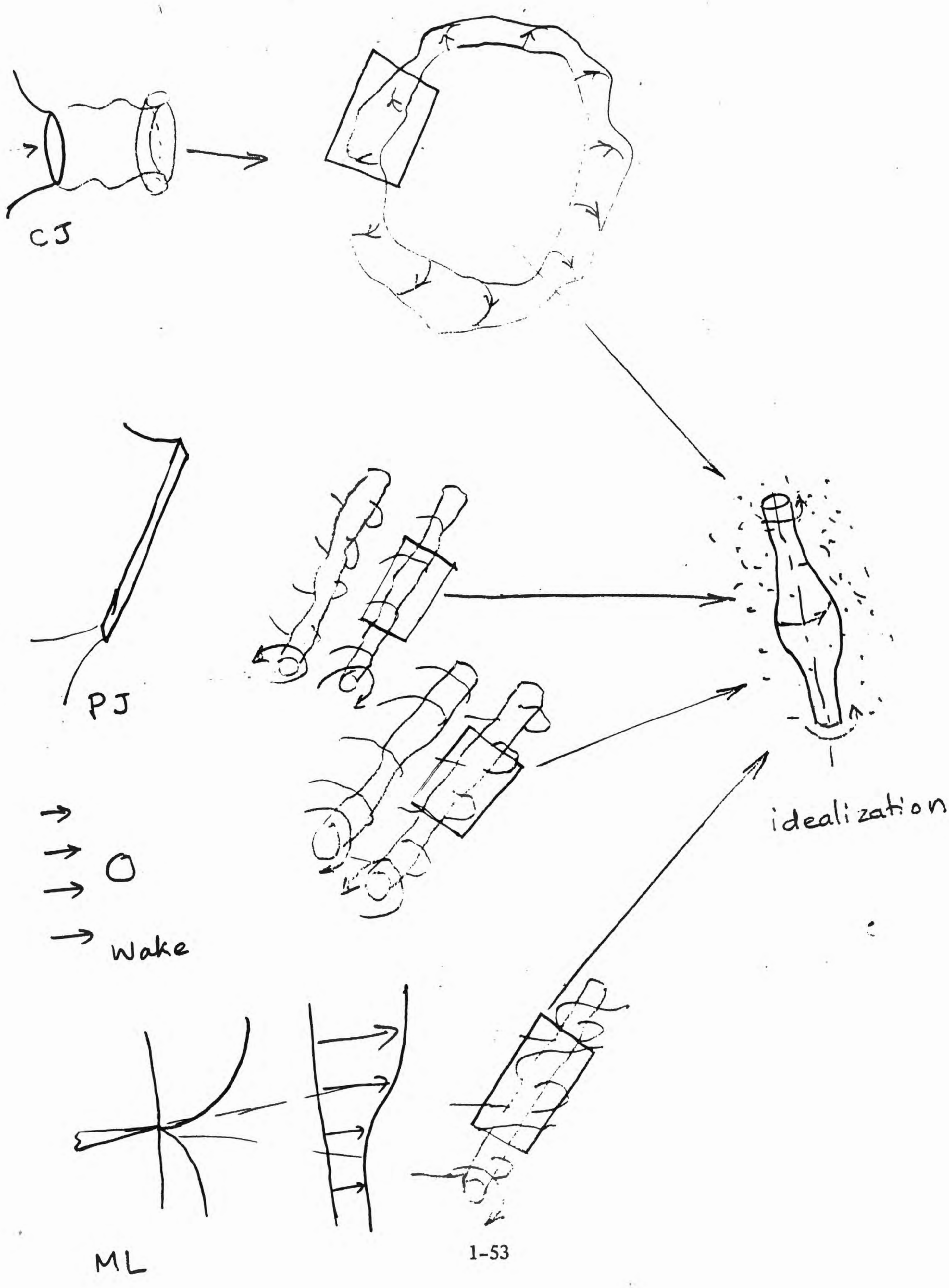
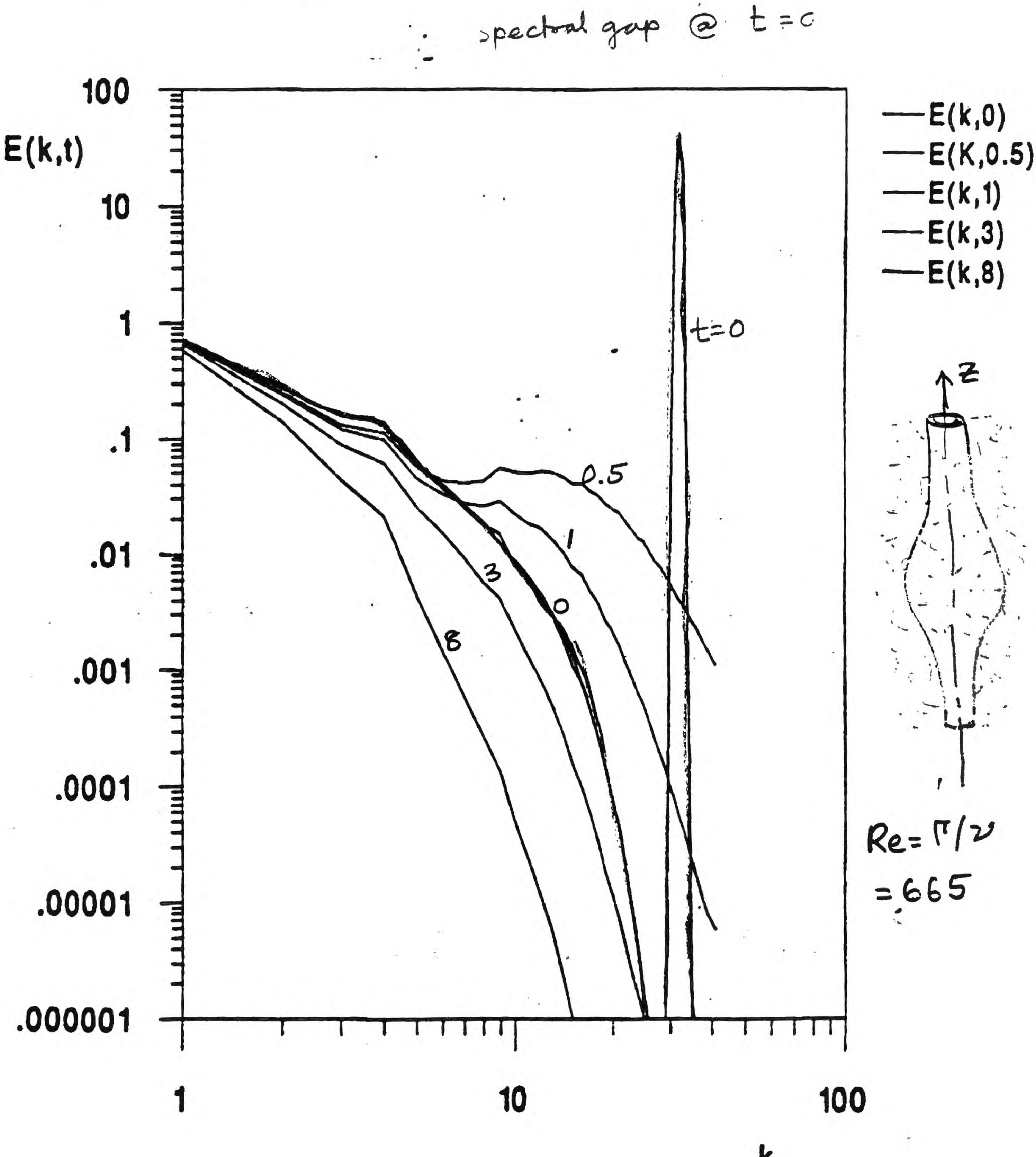
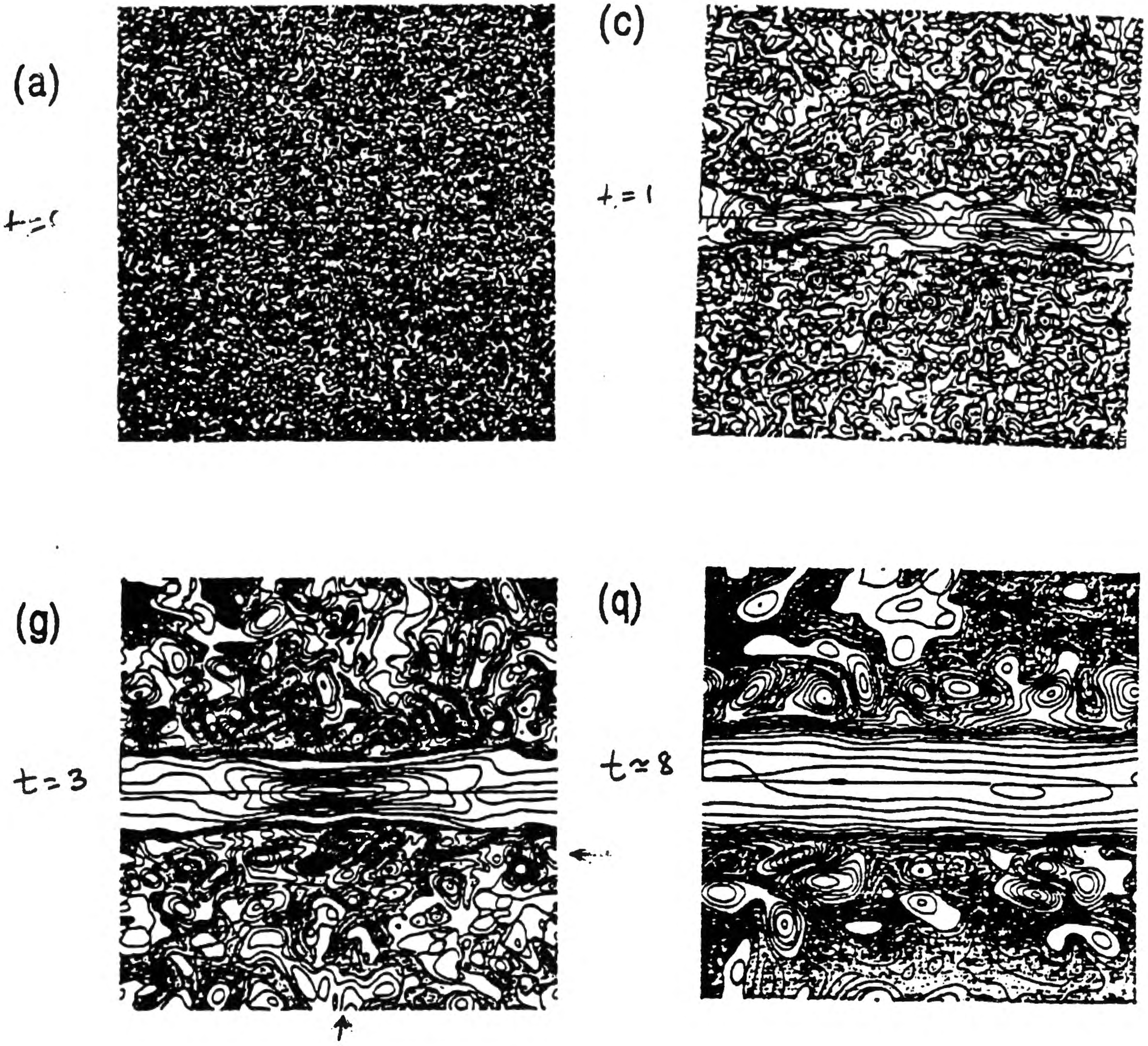


Fig. 19


CJ
PJ
O
wake
idealization
ML

Energy Spectra for Case T1

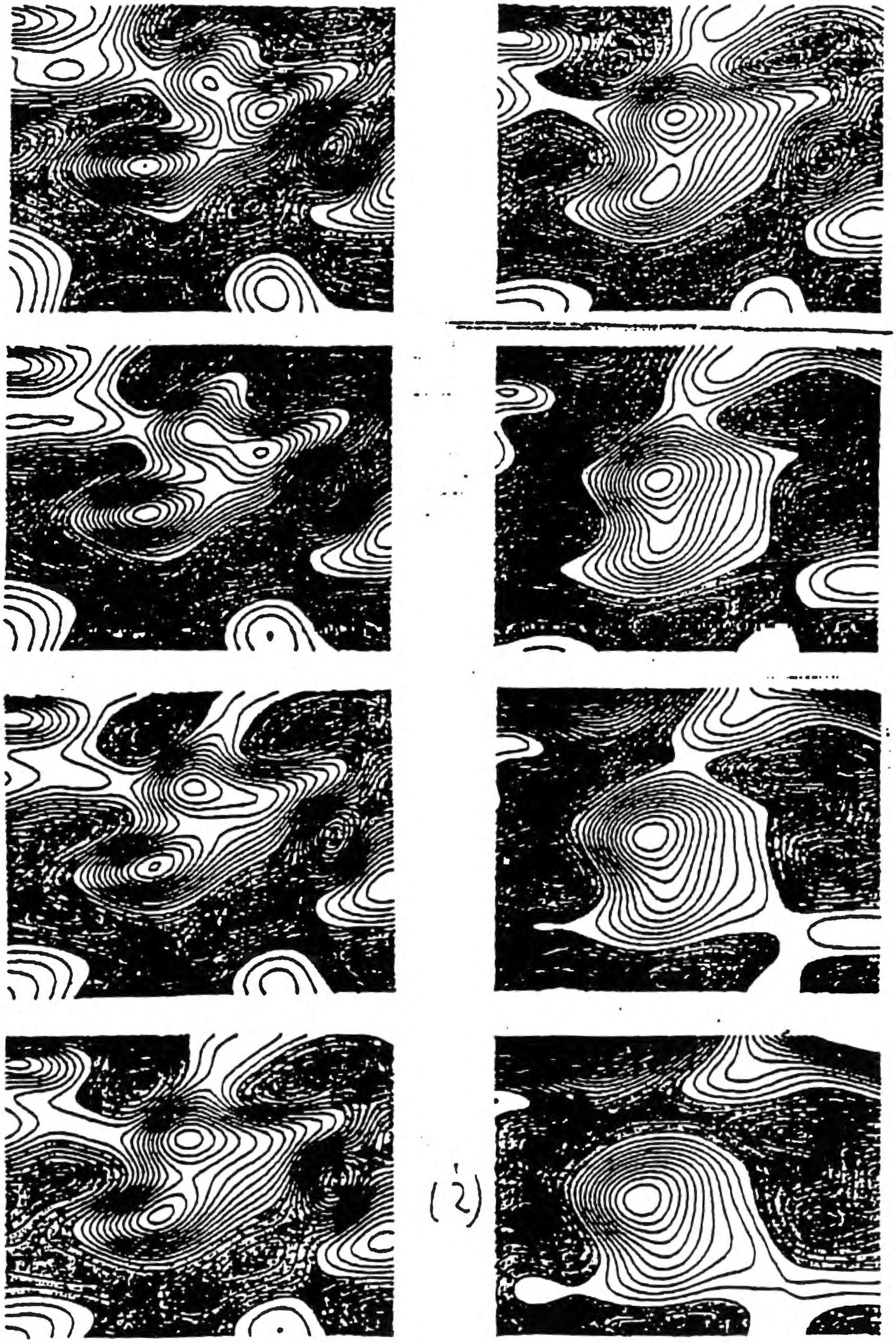




|ω| contours

SS gr and strongest @ C.S boundar

SS Organization by pairing



(1/2)

(A)

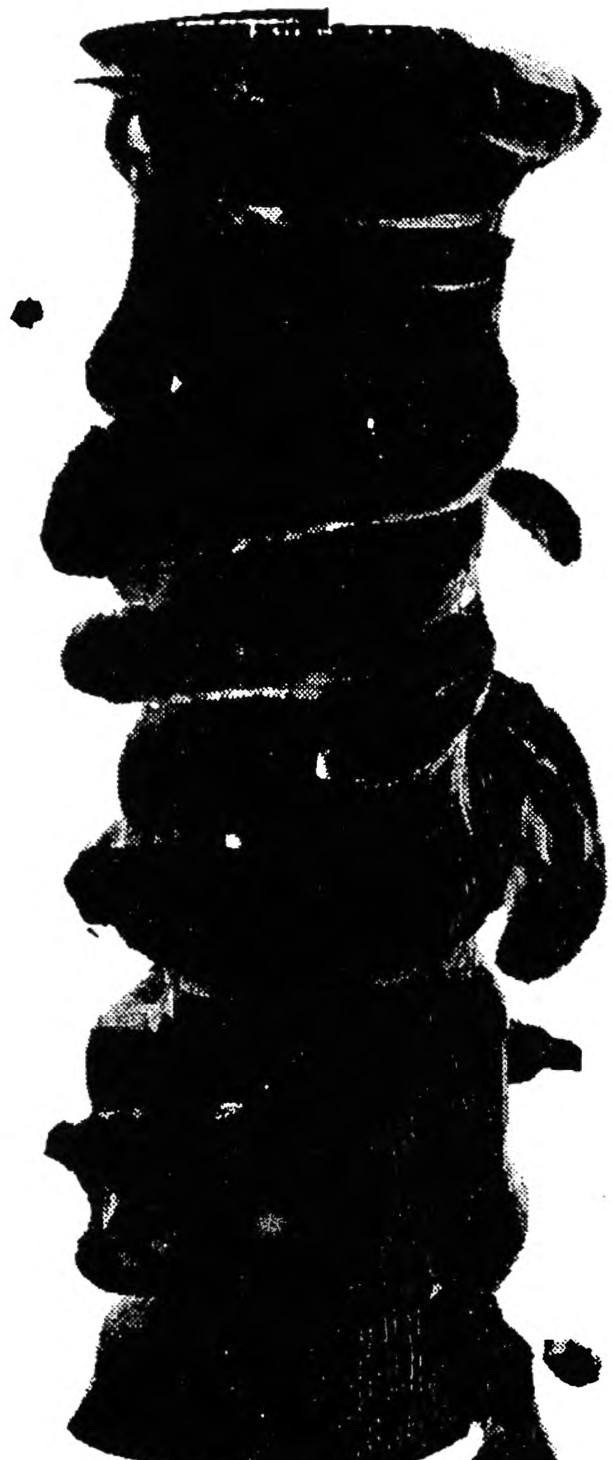
(B)

Fig. 33

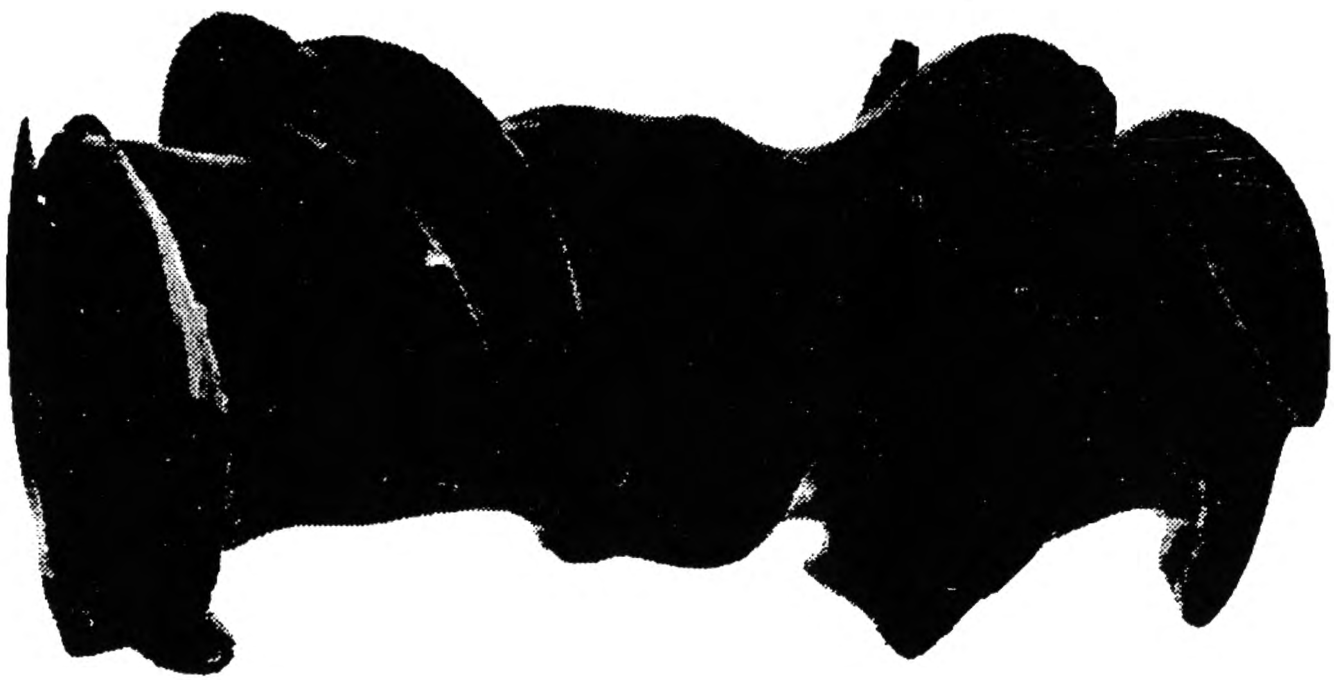
(1)

(3)

6



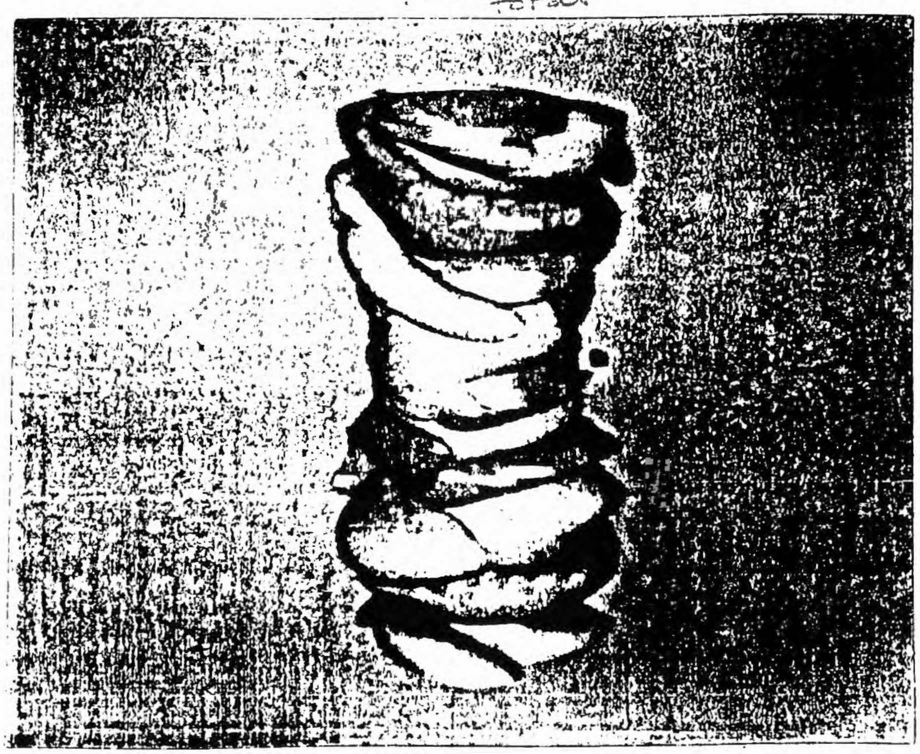
10



Left-handed $|\omega|$

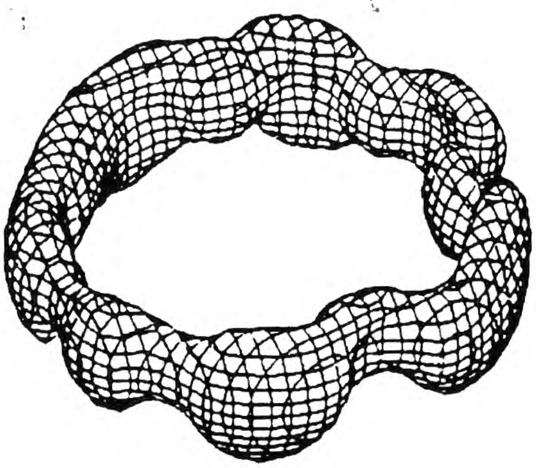
Right-handed $|\omega|$

total

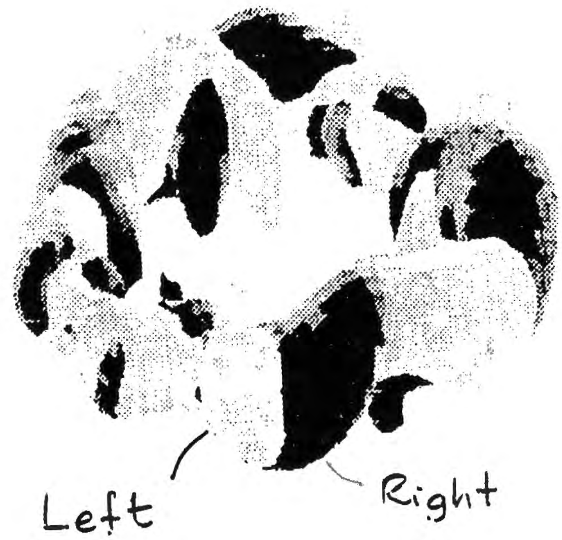


Circular Jet Simulation : Time t=17

$|\omega|$

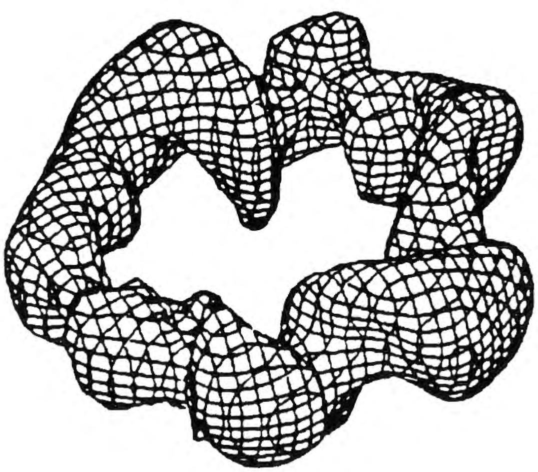


Isovorticity surface, $|\omega|=2$



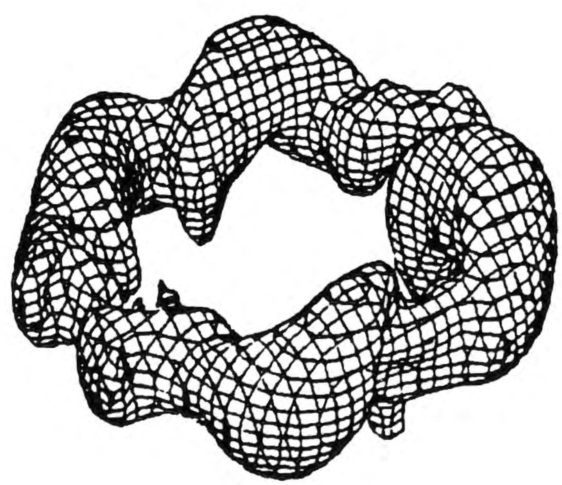
Superposed isosurfaces of right- and left-handed helical vorticity

$|\omega_L|$



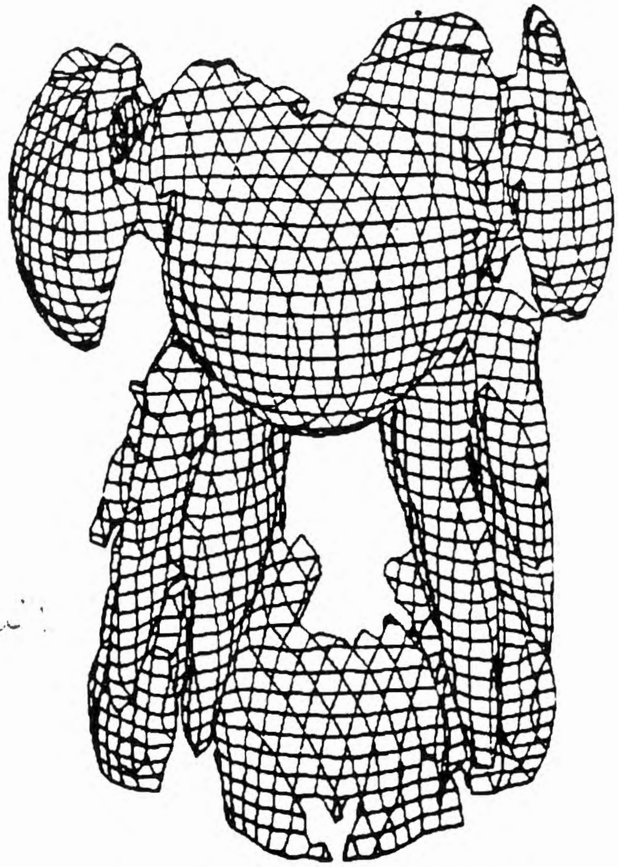
Isosurface of left-handed helical component of vorticity, $|\omega_L|=1.1$

$|\omega_R|$

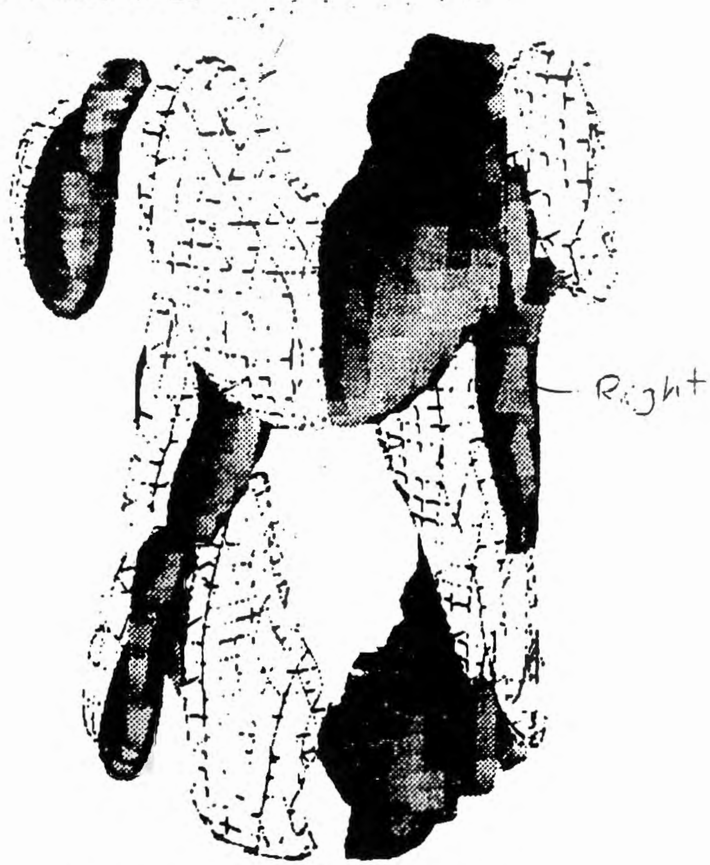


Isosurface of right-handed helical component of vorticity, $|\omega_R|=1.1$

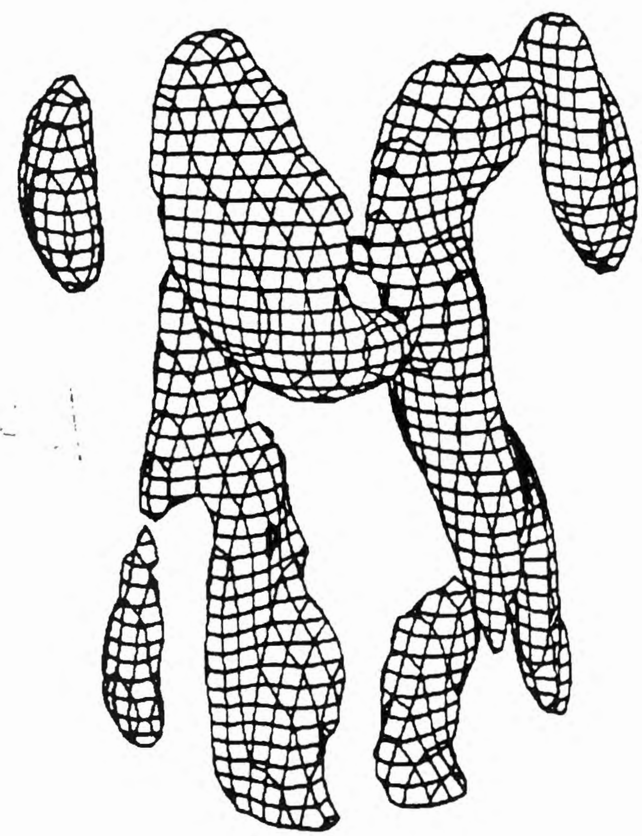
Circular Jet Simulation : Time t=23



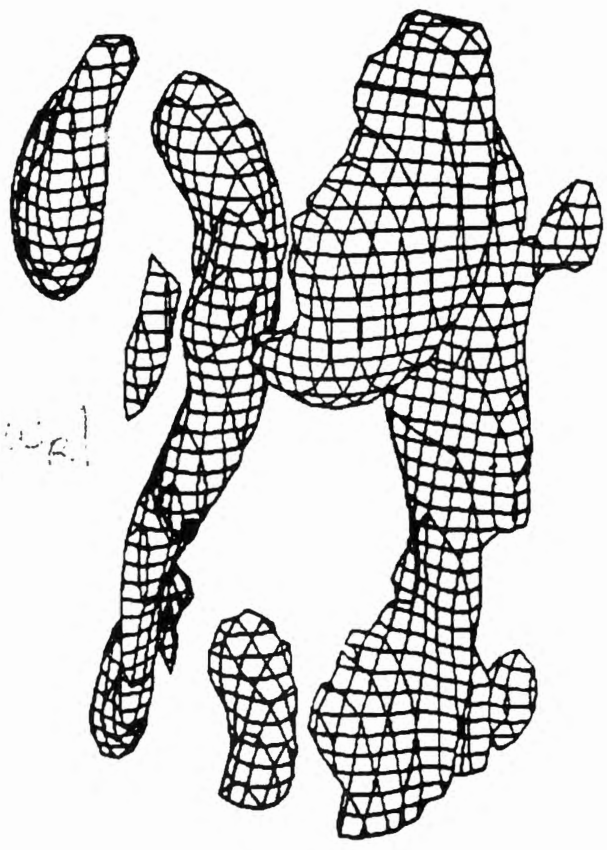
Isovorticity surface, $|\omega| = 2$



Superposed isosurfaces of **right-** and left-handed helical vorticity



Isosurface of **left**-handed helical component of vorticity, $|\omega_L| = 1.6$



Isosurface of **right**-handed helical component of vorticity, $|\omega_R| = 1.6$

Fig. 24

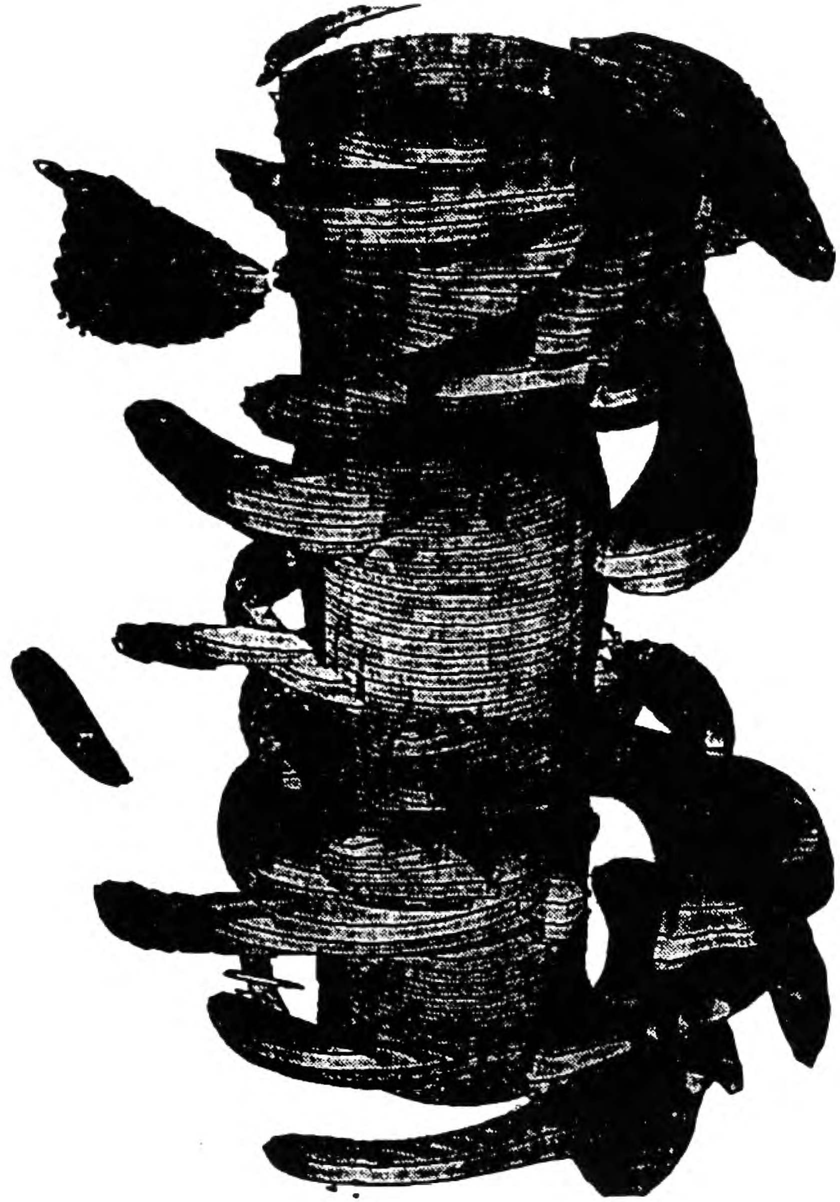
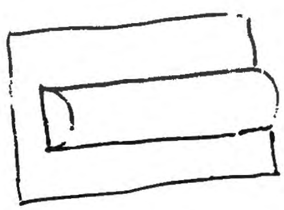


Fig. 25

(l)



(q)

$|\omega|$ contours

$\Gamma/\nu = 665$

$t = 8$

Fig. 23

(A)

$\Gamma/\nu = 2500$

after $t \simeq 8$

$\Delta t = 4$

(B)

$\Gamma/\nu \simeq \infty$

after $t = 8$

$\Delta t = 4$

Fig. 37

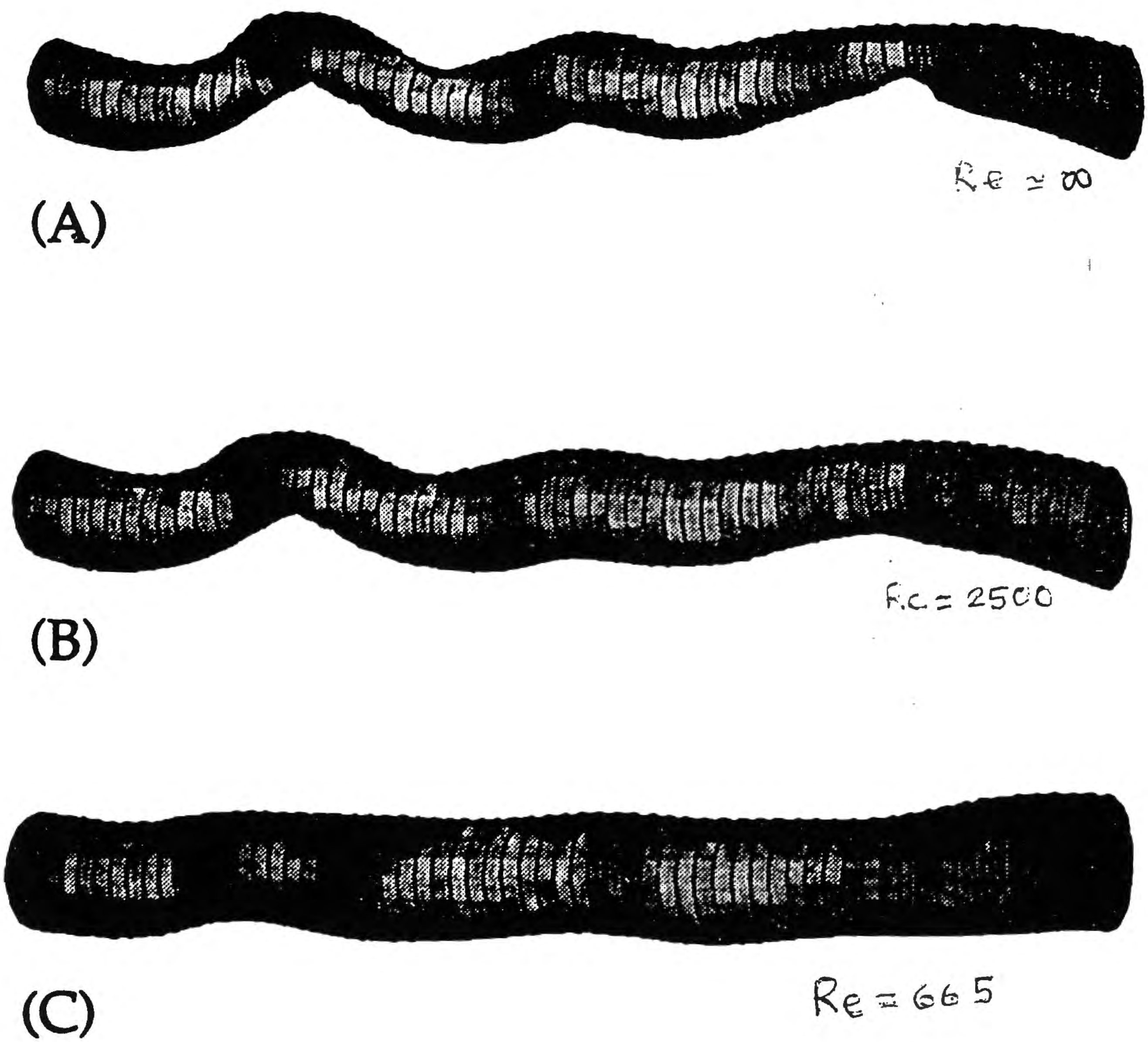
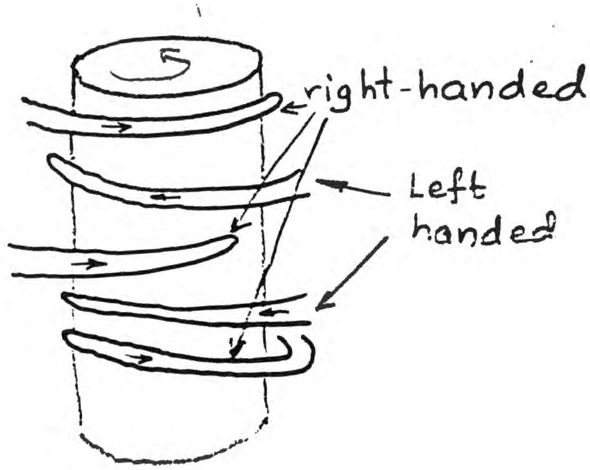
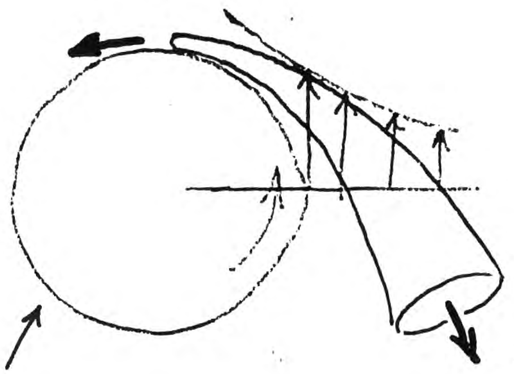
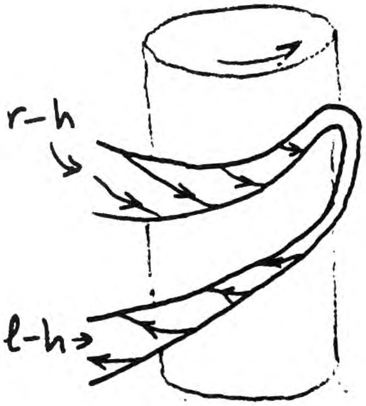


Fig. 38

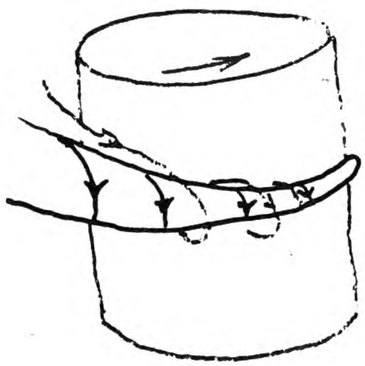




polarization
by stretching

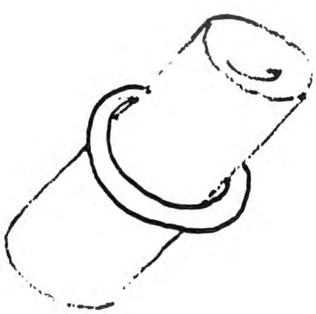


right & left
polarization

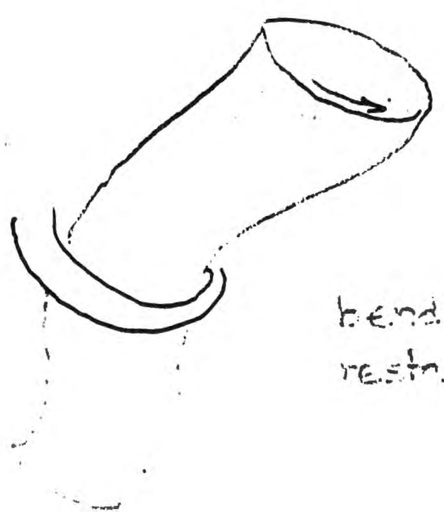


entrainment
by ss

growth of ss by
pairing & ent.

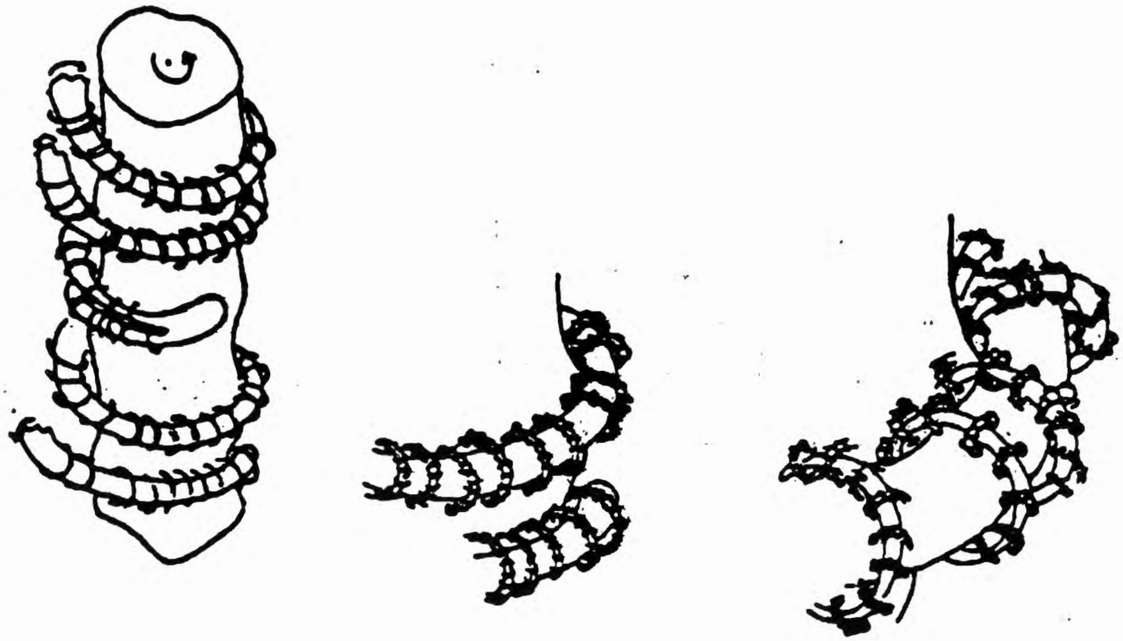


no stretching
of ss



bending [illegible]
restrict [illegible]

A cascade scenario



A hierarchy of smaller structure (fractal)

LS preferentially oriented → also SS;

local isotropy questionable.

$|\omega|$ and ϵ fractal structure

Helical waves (right and left handed)
separate spatially

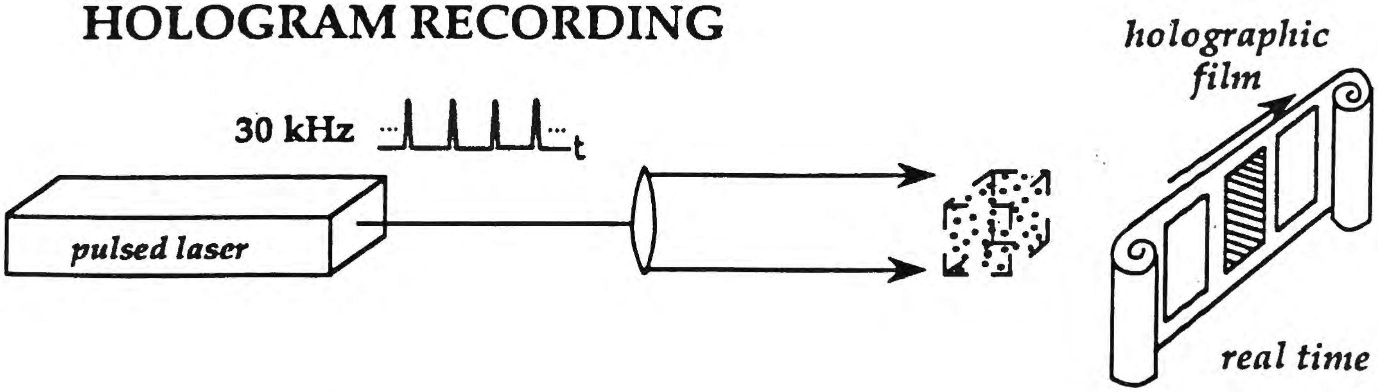
They characterize CS

Breakdown to turbulence is
more organized than presumed.

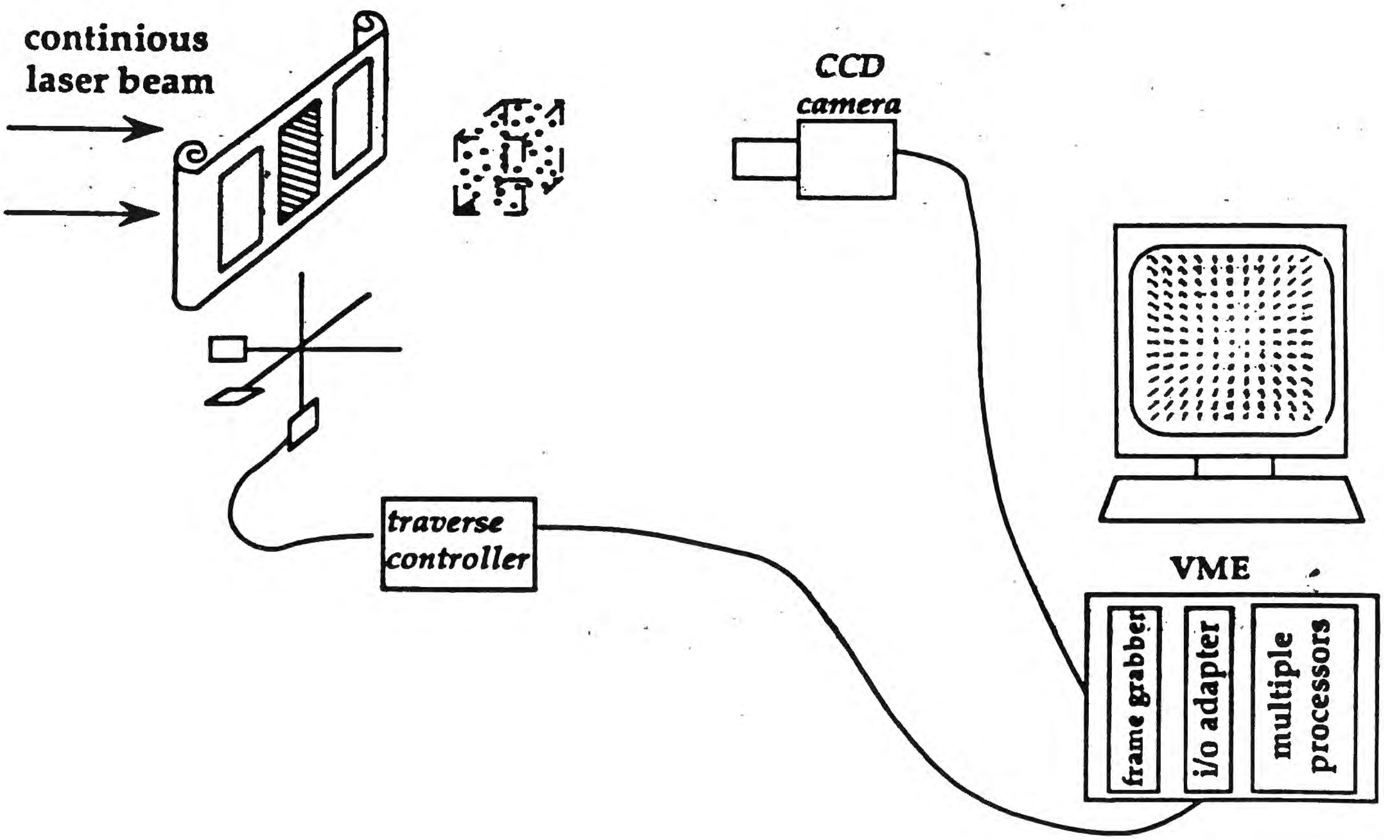
Planning expts
using holographic particle velocimetry
ESR velocimetry

Holographic Particle Velocimetry

HOLOGRAM RECORDING



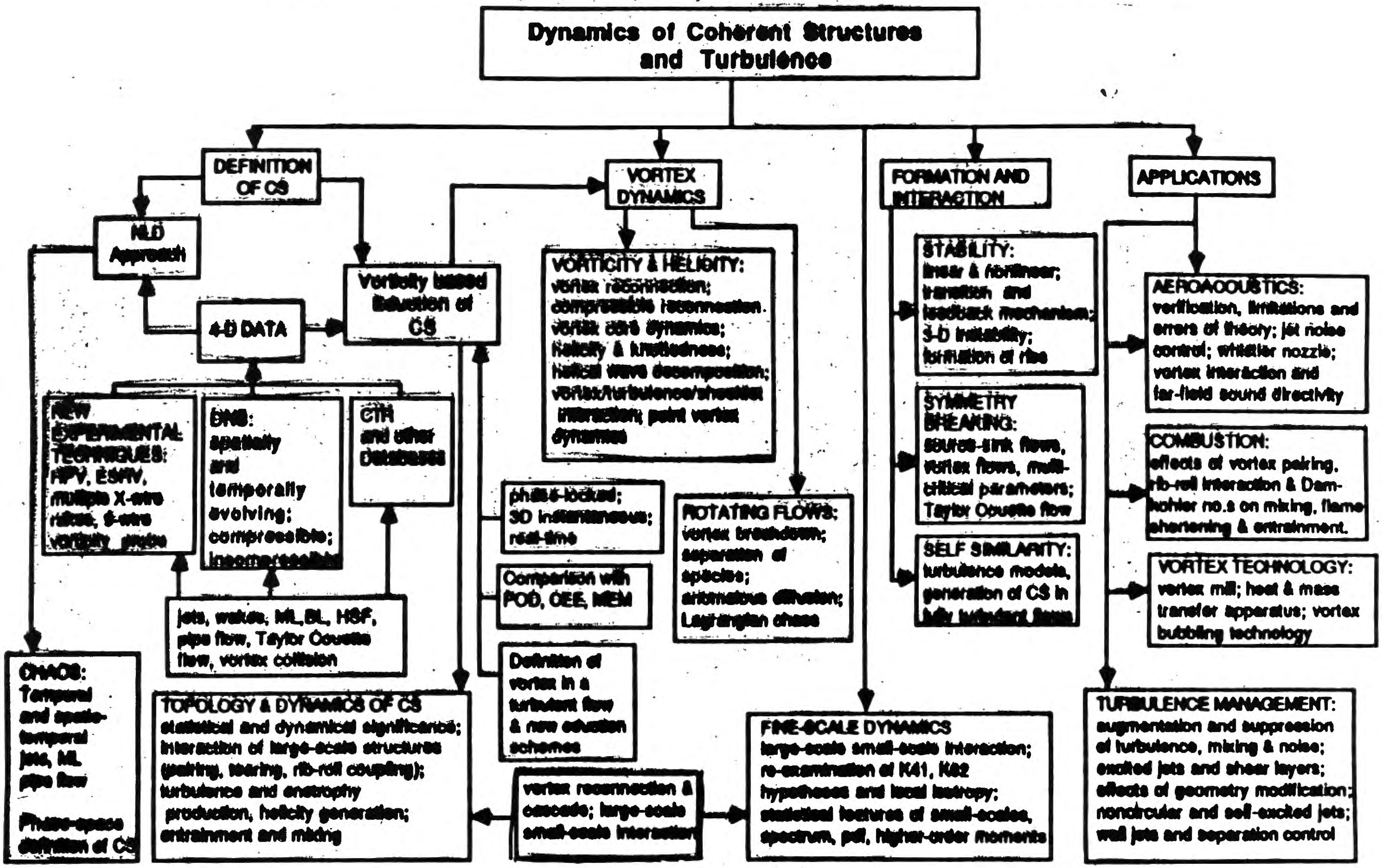
RECONSTRUCTION & DATA PROCESSING



Some conclusions

1. Core dynamics very important
2. Nonuniform Core size sets up wavepackets moving faster at higher Re, freq → const. as Re → ∞
3. CD can be explained qualitatively by coupling of swirl and meridional flow
4. But complex helical wave decomposition (HD) is more effective; explains CS evolution better
5. CS organizes SS turb. into polarized structures which entrain and spatially grow (by pairing) and separate into left and right handed struct.
6. SS can feedback energy to CS by exciting bending waves, thus their own survival.
7. LS/SS (conceding scale separation) are intimately coupled: question local isotropy.

Aerodynamics & Turbulence Laboratory, University of Houston



Abbreviations: BL - Boundary Layer; CEE - Conditional Eddy Estimation; DNS - Direct Numerical Simulation; ESRV - Electron Spin Resonance Velocimetry; HPV - Holographic Particle Velocimetry; HSF - Homogeneous Shear Flow; K41, K62 - Kolmogorov's 1941 & 1962 hypotheses for turbulence; MEM - Maximum Entropy Method; ML - Mixing Layer; NLD - Nonlinear Dynamics; POD - Proper Orthogonal Decomposition

2. Renormalization Group Theory for Turbulence Transport Modeling

Steven A. Orszag
Princeton University

SEMINAR NOTICE

RENORMALIZATION GROUP THEORY FOR TURBULENCE TRANSPORT MODELING

STEVEN A. ORSZAG

Hamrick Professor of Engineering and

Director and Professor of Applied and Computational Mathematics

Princeton University

In this talk, we shall describe the development and application of renormalization group (RNG) turbulence transport models with non-equilibrium rate-of-strain effects included. A wide variety of examples will be given, including turbulent flows, heat transfer, and pre-mixed combustion in step, cylinder, turn-around bend, valve, constricted pipe, blunt plate, and other geometries. The robustness of the modeling for massively separated, non-equilibrium, and swirling flows will be discussed. The relationship of transport modeling to full Navier-Stokes solutions and large-eddy simulations will also be discussed, especially in the context of describing coherent structure dynamics.

Thursday, 16th July 1992

Conference Room, Bldg. 990 (6th Floor)

Time: 10:30 AM

POC: Dr. Promode R. Bandyopadhyay (Code 804; x2588)

Gosman + Ahmed (1987)

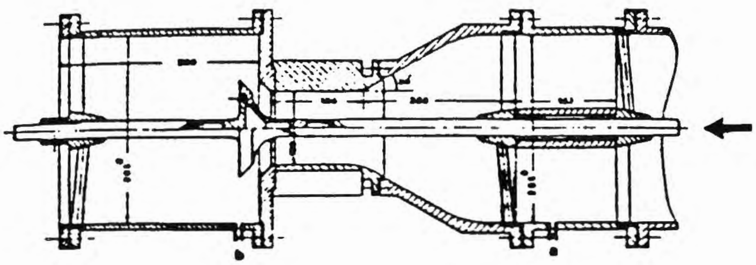


Fig 1(a) Details of the test section

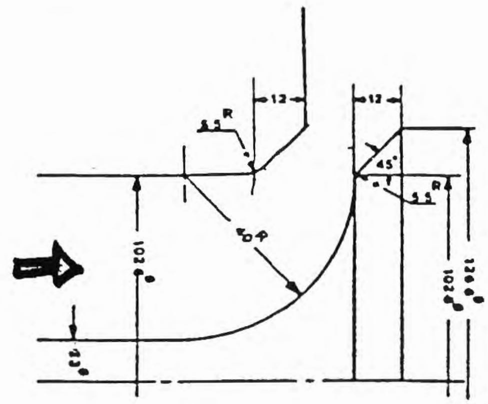


Fig 1(b) Details of the valve/port assembly

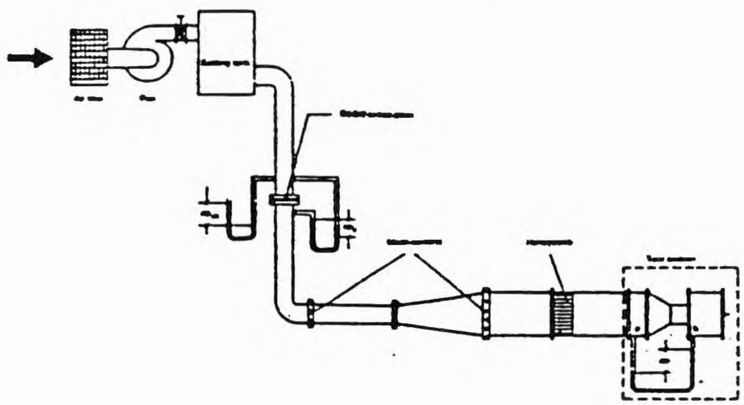


Fig 2 Schematic layout of the test rig

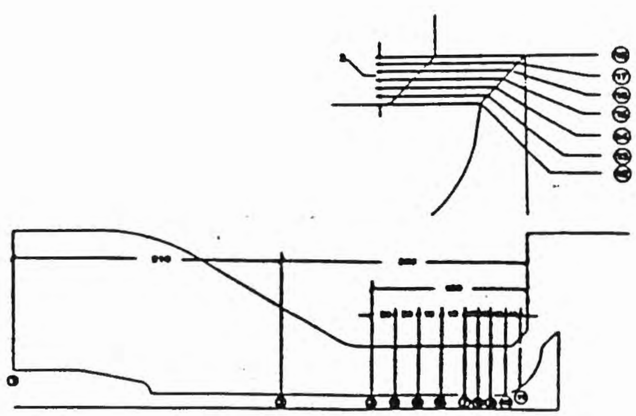
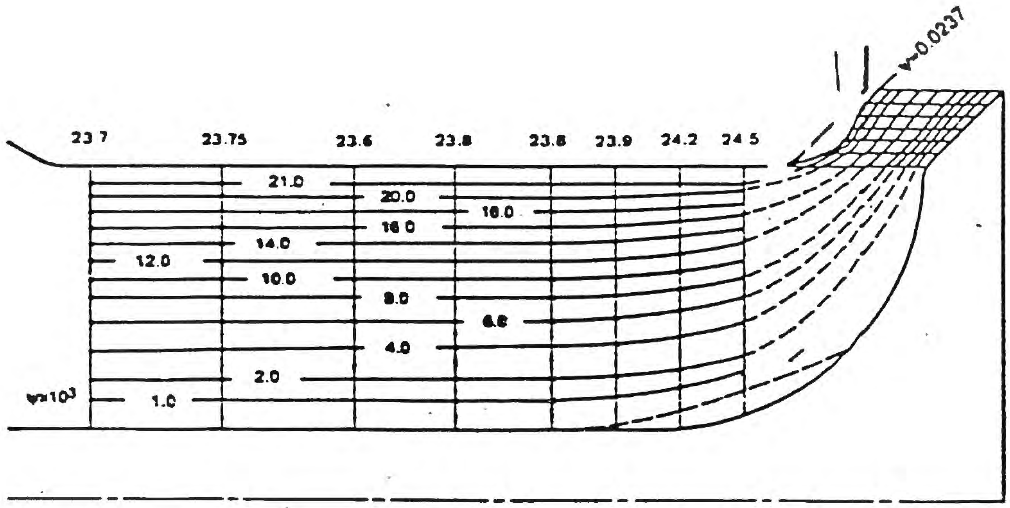


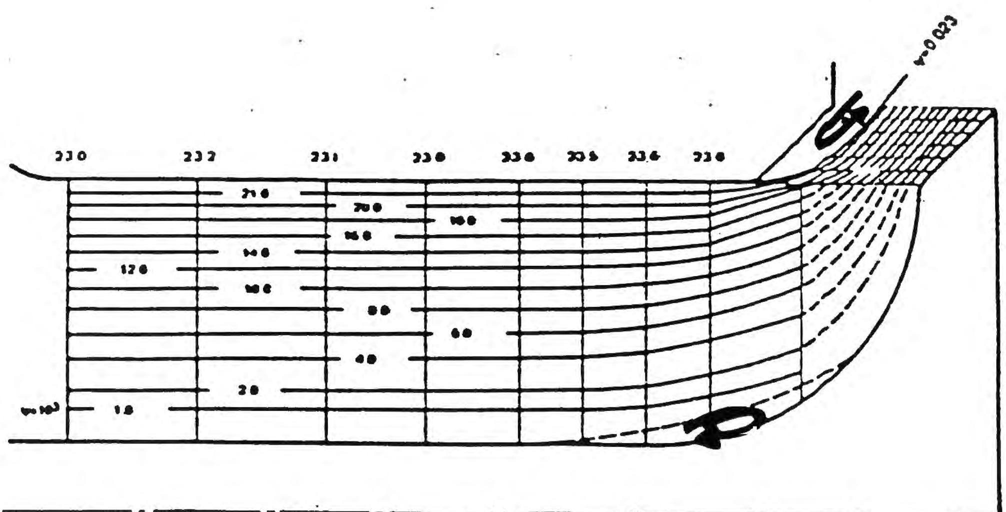
Fig 3 Locations of measuring traverses

Gosman + Ahmed (1987)

Flow Visualization

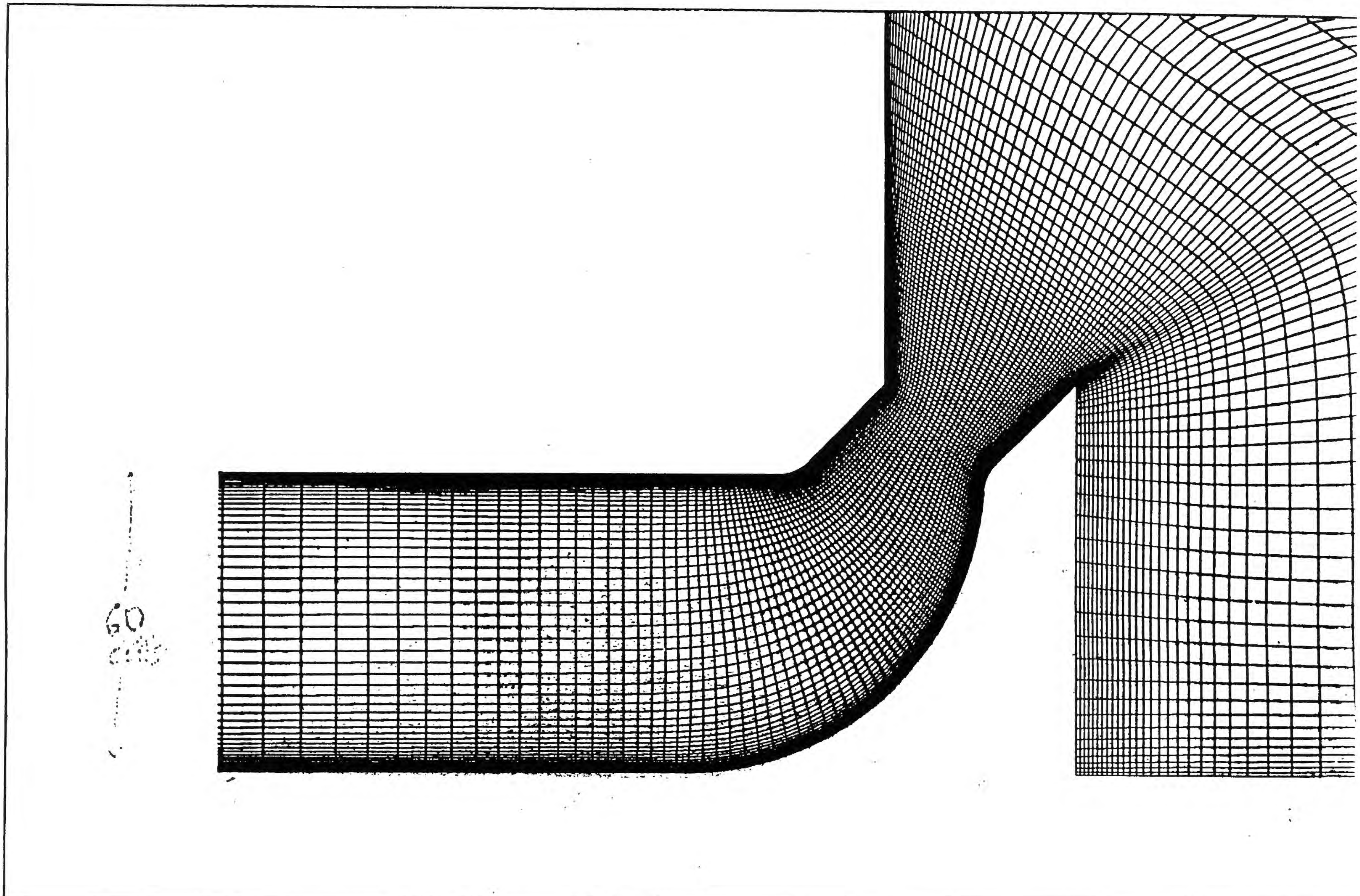


(d) L* - 0.20



(e) L* - 0.25

Fig 7 (concluded)

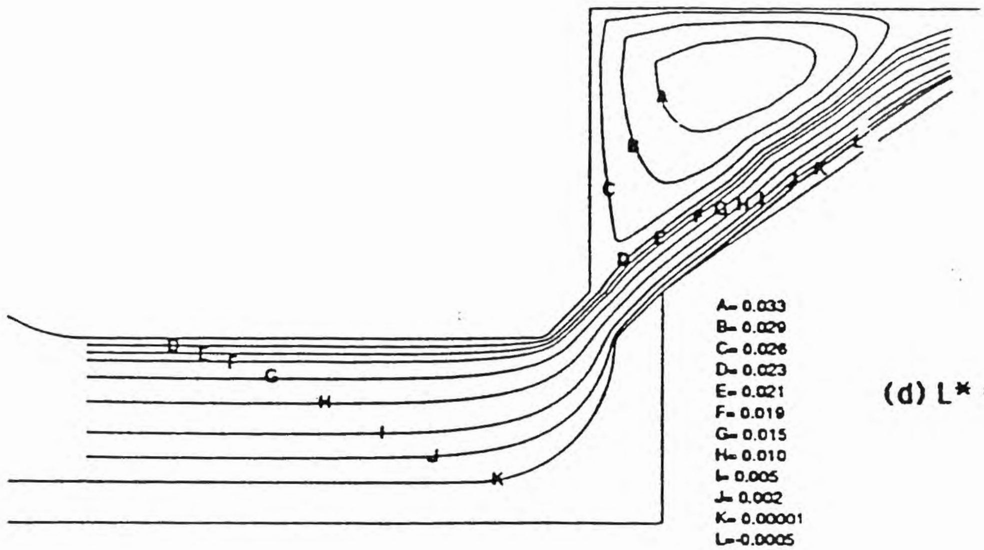


Turbulent flow in a valve-port geometry
Grid

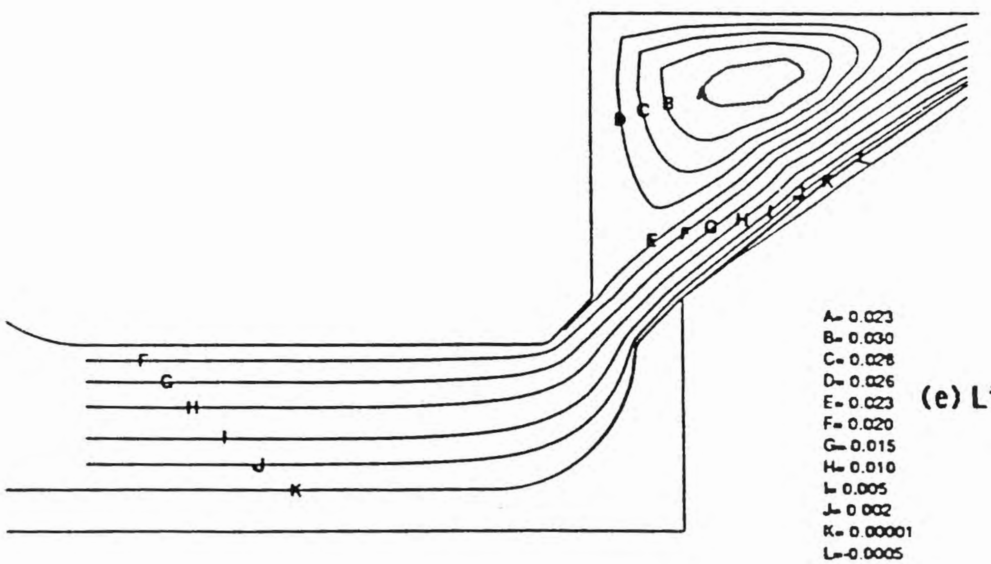
05/28/92
Fluent 4.1
Fluent Inc

Gosman + Ahmed (1987)

Standard k-ε model calculations

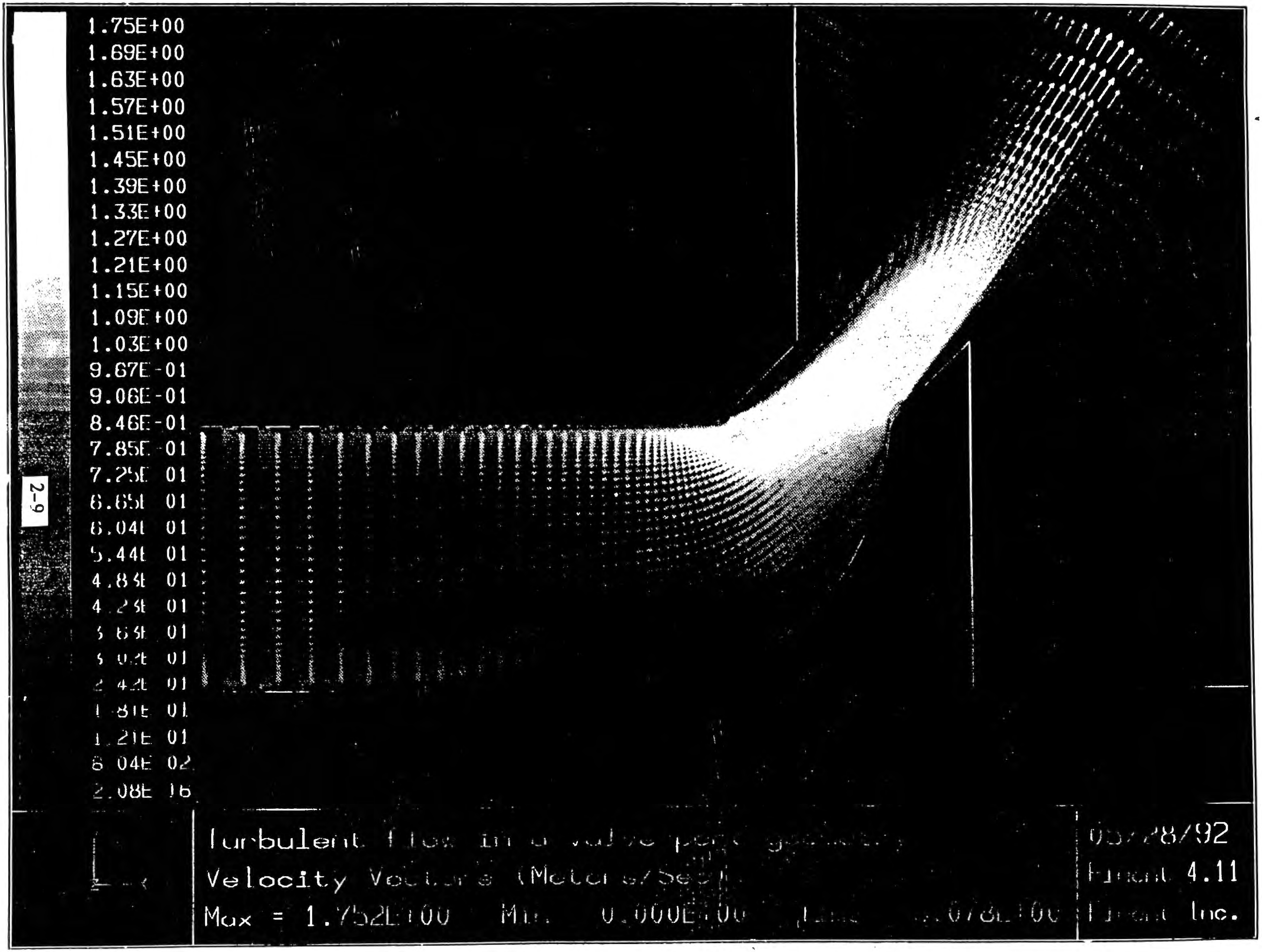


(d) L* = 0.20

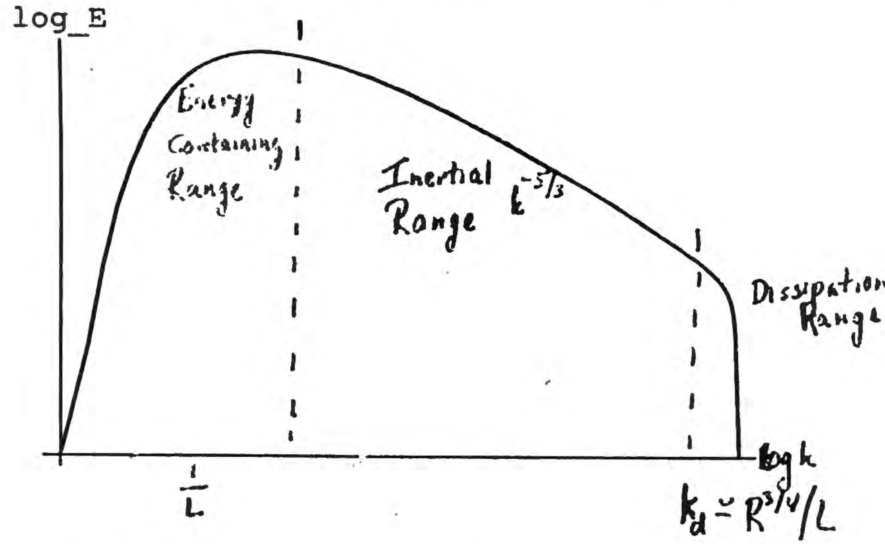


(e) L* = 0.25

Fig 9 (concluded)


1.75E+00
1.69E+00
1.63E+00
1.57E+00
1.51E+00
1.45E+00
1.39E+00
1.33E+00
1.27E+00
1.21E+00
1.15E+00
1.09E+00
1.03E+00
9.67E-01
9.06E-01
8.46E-01
Turbulent
Velocity
Max = 1.752E+00
05/28/92
Fluent 4.11
Fluent Inc.

WORK REQUIREMENTS FOR TURBULENCE COMPUTATIONS



Three-Dimensional Turbulence —

Storage $O[(R^{3/4})^3] = O[R^{9/4}]$

Work $O[(R^{3/4})^4] = O(R^3]$

Two-Dimensional "Turbulence" —

Storage $O[(R^{1/2})^2] = O[R]$

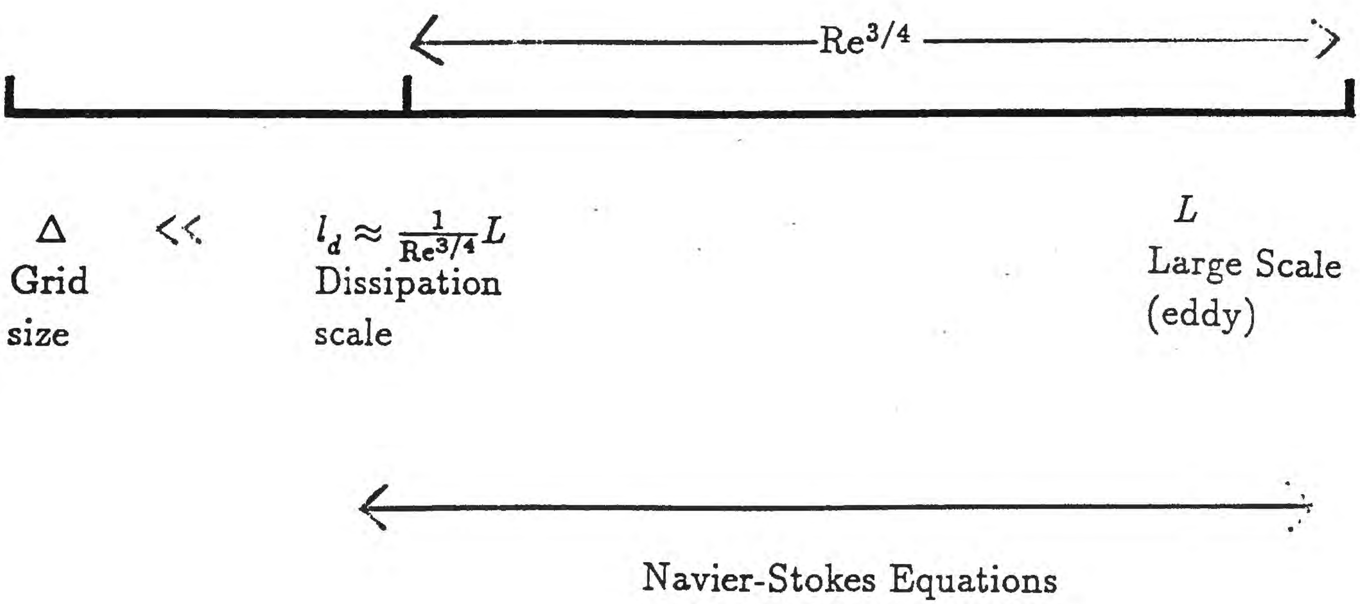
Work $O[(R^{1/2})^3] = O[R^{3/2}]$

GOAL OF TURBULENCE THEORY:

REDUCE THESE STORAGE AND WORK REQUIREMENTS

DIRECT NUMERICAL SIMULATION

DNS



CM2 Simulation of Homogeneous Turbulence

–Advanced Computing Laboratory–
–Los Alamos National Laboratory–

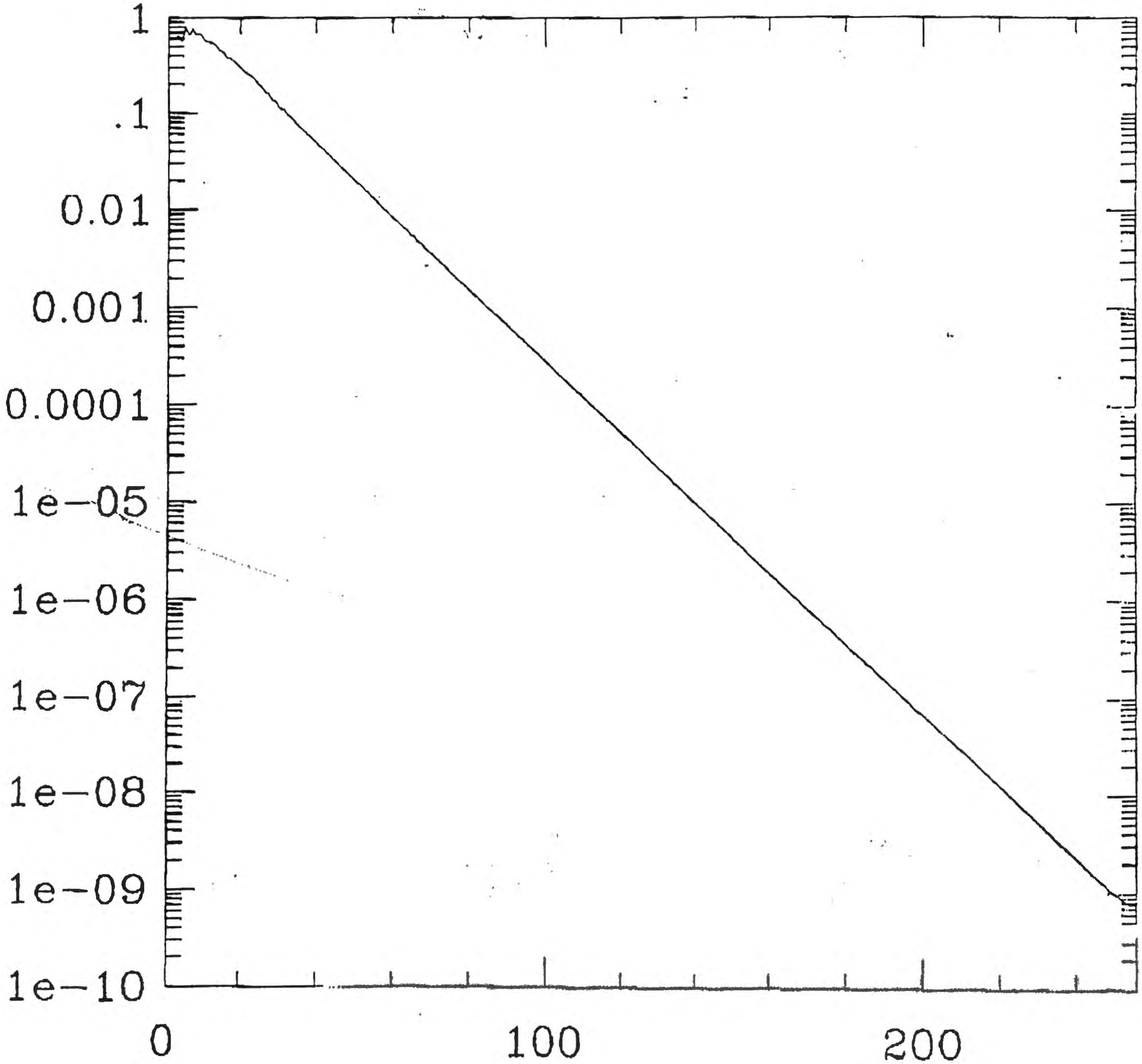
Shiyi Chen, Xiaowen Shan	LANL
Robert Kraichnan	
Zhen-Su She, Steven Orszag	Princeton

$512 \times 512 \times 512$ Spectral Code ($\approx$ 1+ min/timestep)

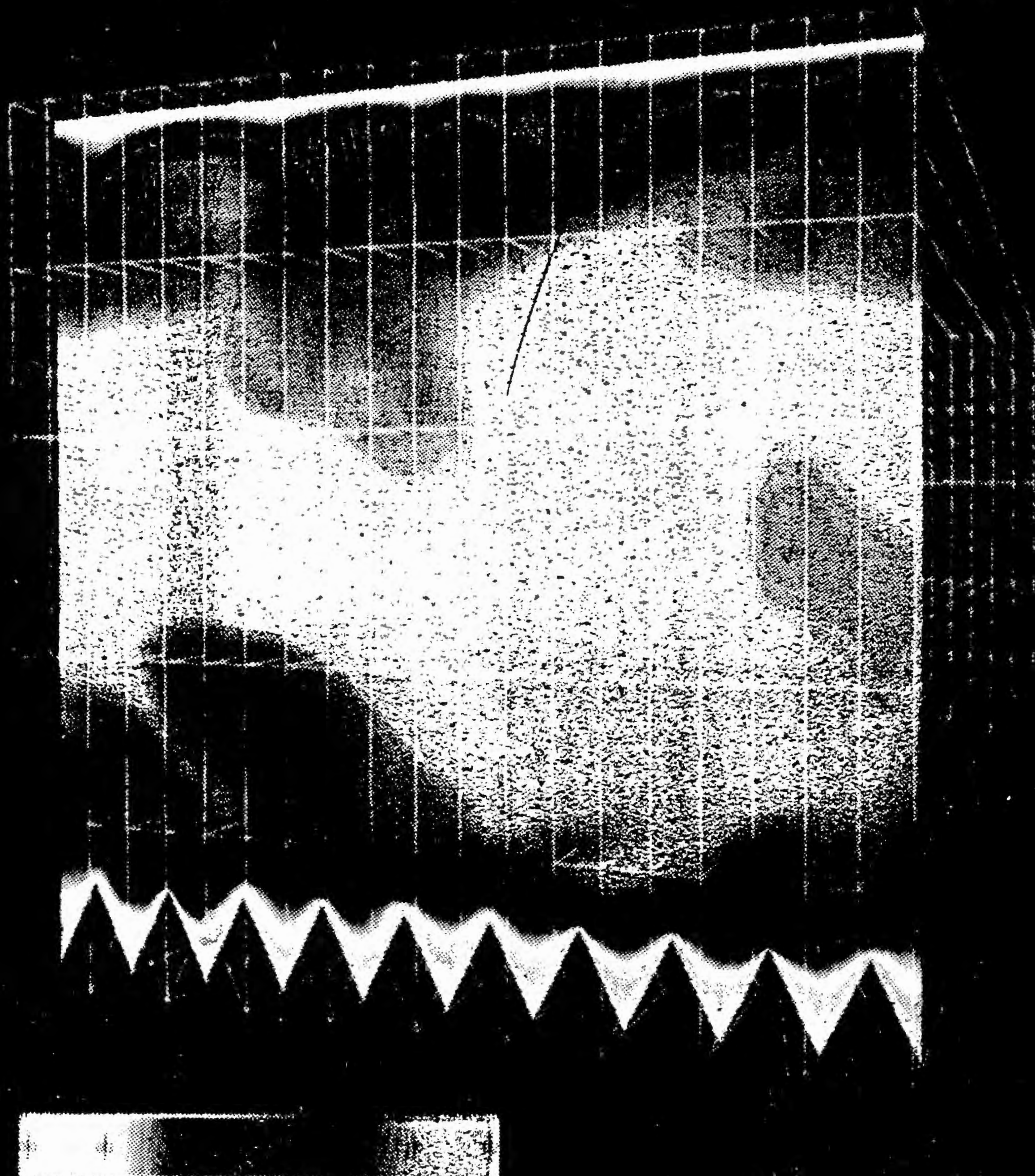
Runs to date (11/24/91): $R_\lambda = 36, 70, 160$

$$\frac{E(k)}{k^{-5/3}\left[1+\beta(k/k_d)^{14/3}\right]}$$ plot : lin - log

$\beta = 0.4$

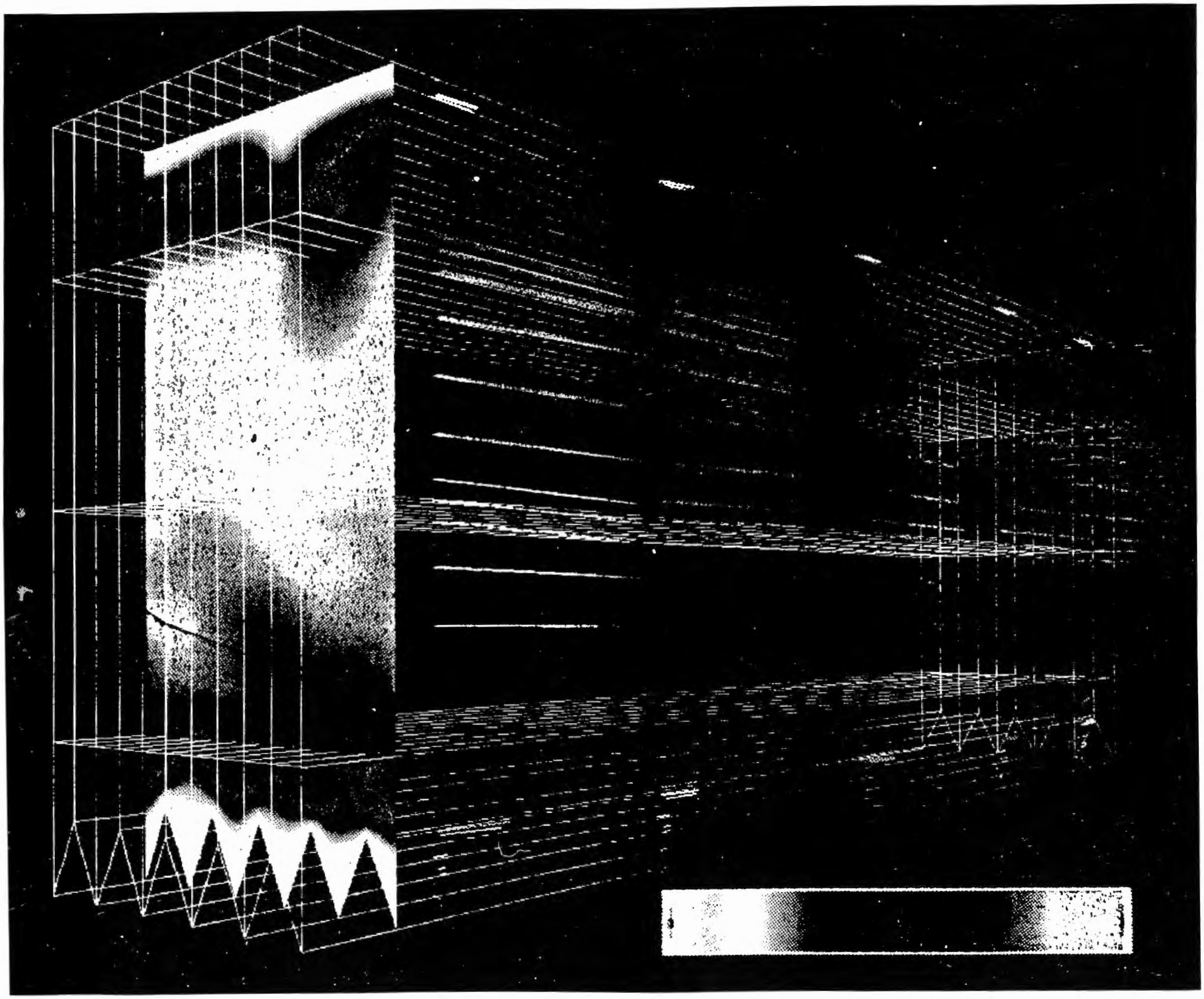


DNS of Turbulent Flow Over Riblets



Re = 3500

Streamwise Velocity Contours



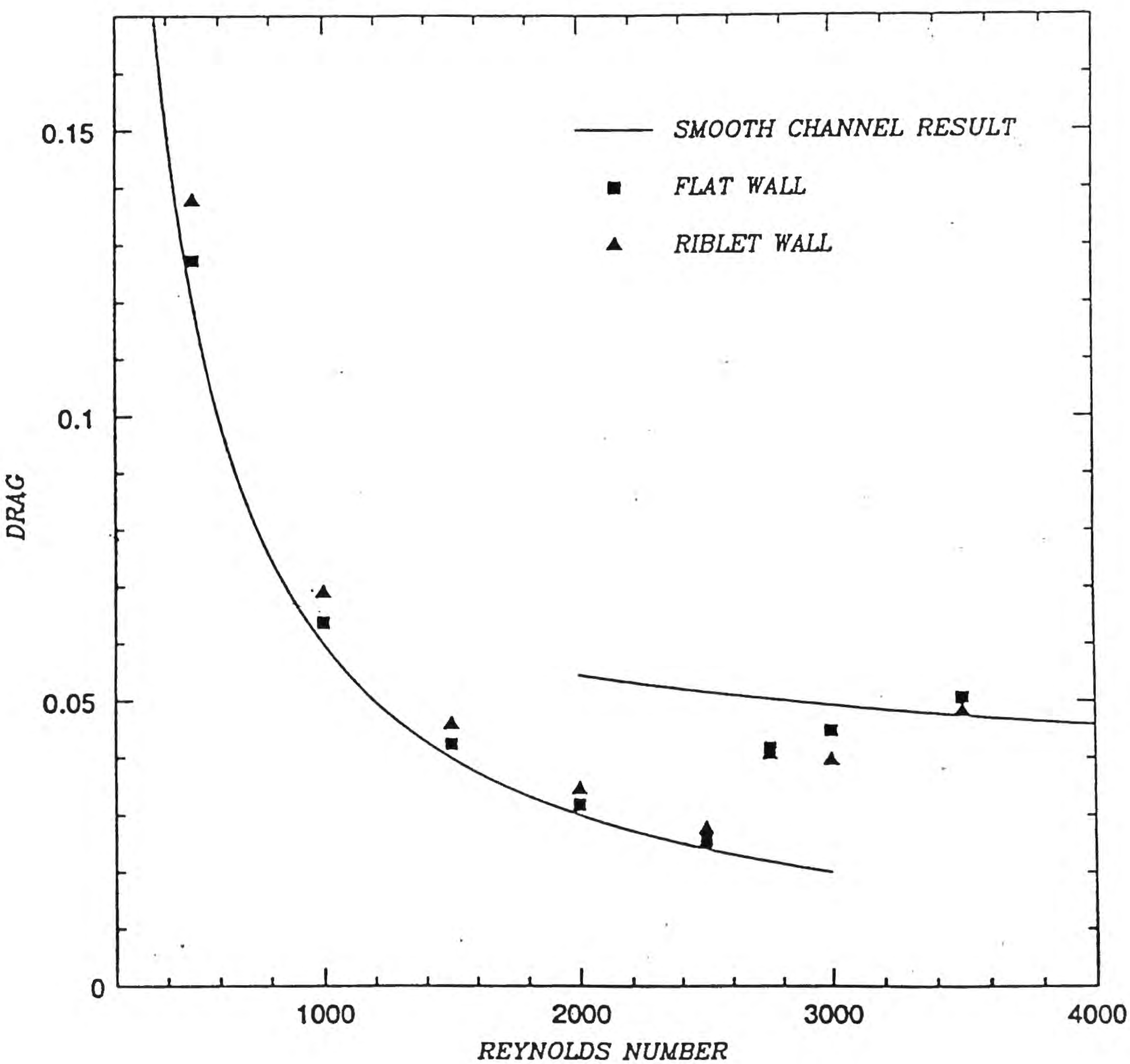


Figure 52: Drag on each wall vs. Reynolds number for riblet channel simulation.

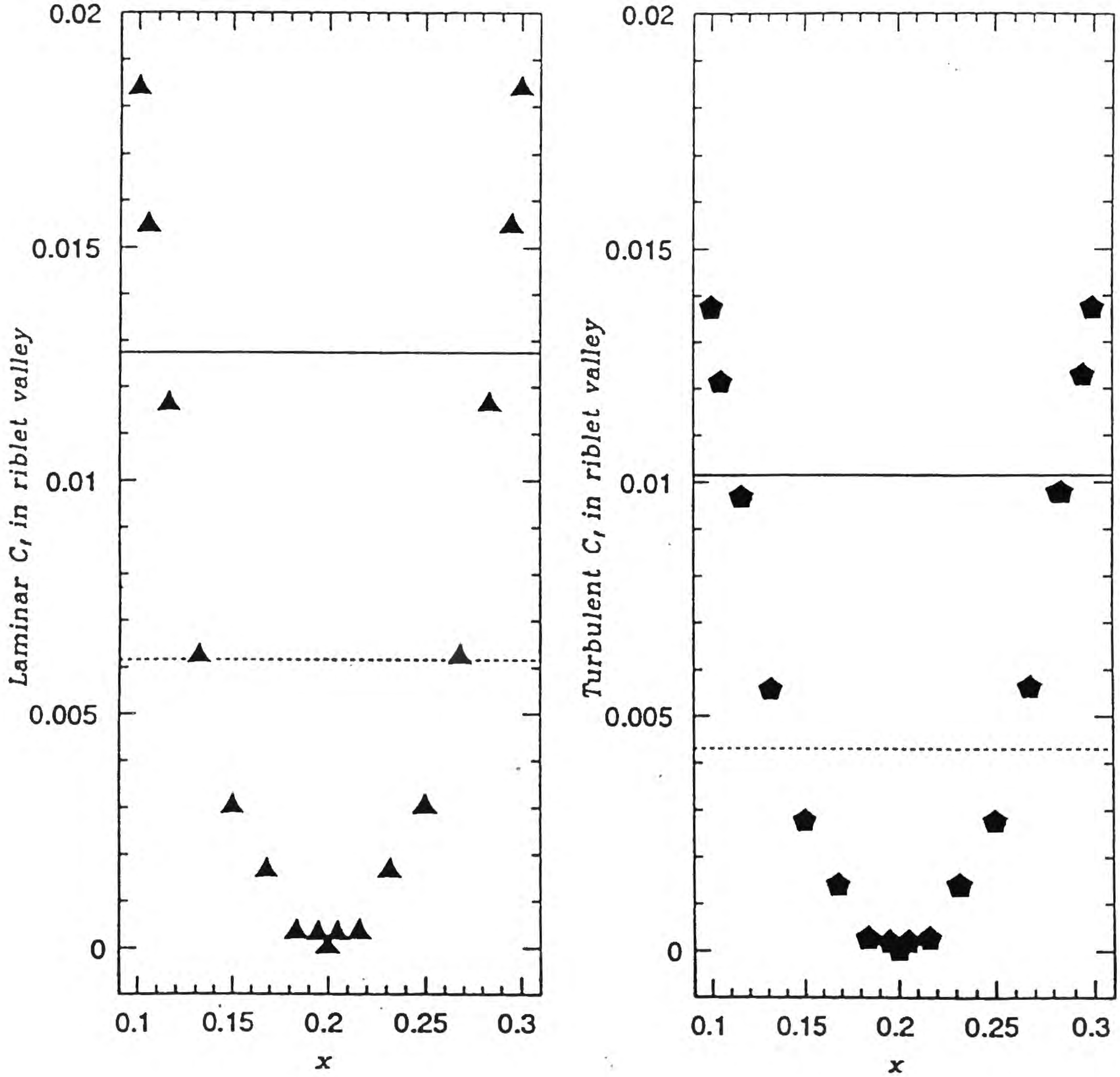
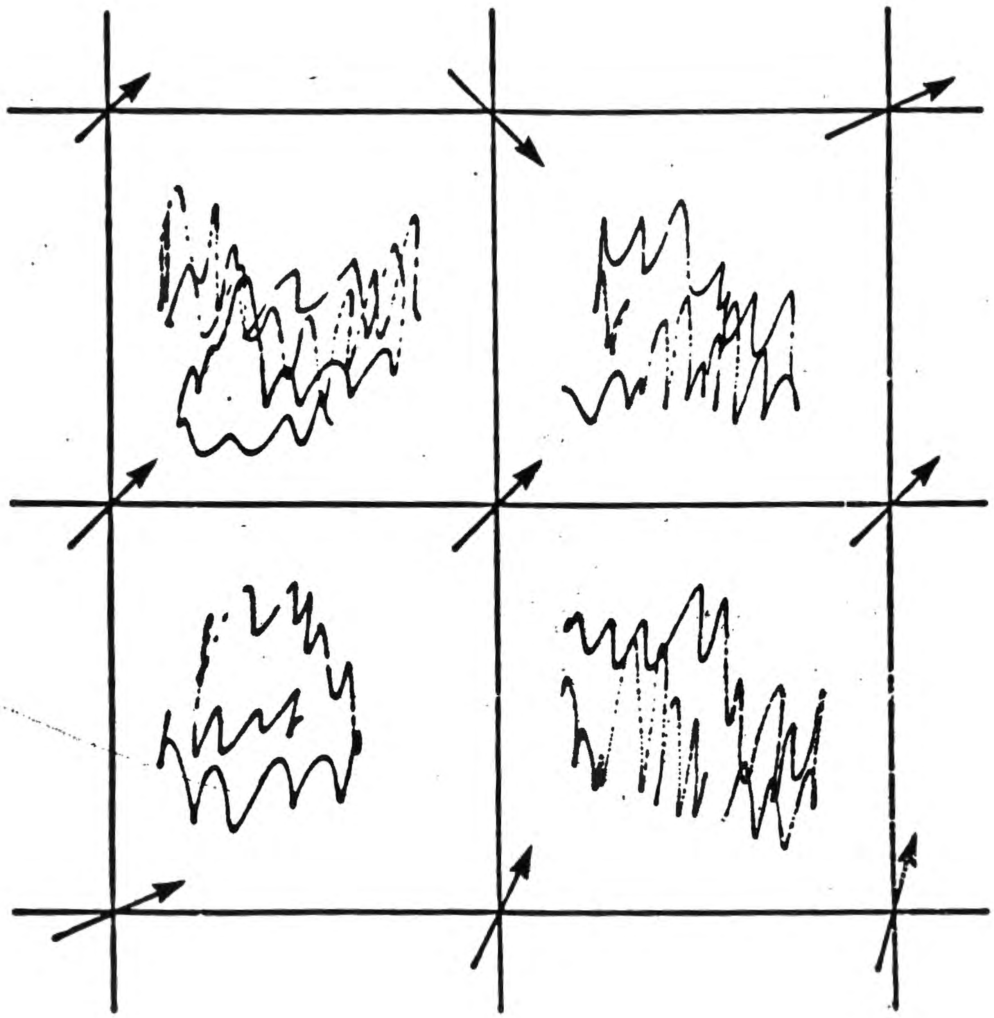


Figure 51: Comparison of laminar and turbulent local skin friction distribution inside triangular riblet valley ($Re = 1000, 3500$). Symbols and lines are described in the text.

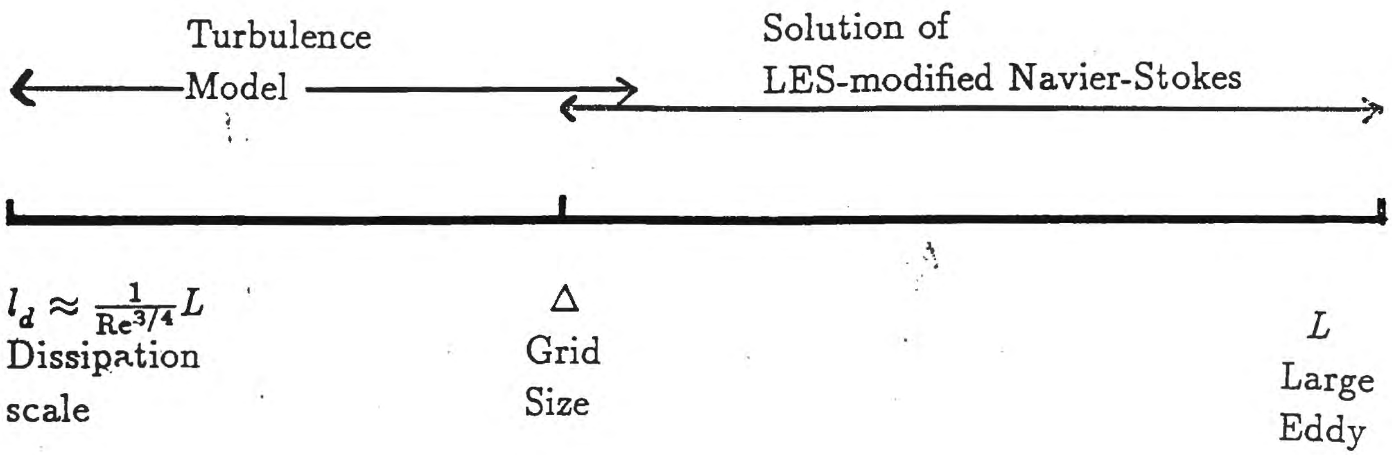
SUBGRID TURBULENCE



Effects of Subgrid Turbulence
- ·Turbulence Dissipation
- ·Turbulence Production - Random Forcing

LARGE-EDDY SIMULATION

LES



Length-scale model
for 'subgrid' stresses
$\nu_\Delta |\nabla U_{\text{supergrid}}|$

Result: $\underline{U_{\substack{\text{supergrid} \\ \text{large eddy}}} \text{ random on scales } \gtrsim \Delta}$

LARGE EDDY MODELS OF TURBULENCE

— Navier-Stokes Equations Solved at Large (Super-Grid) Scales

— One-Point (Eddy Viscosity, K-ε Model) Closure for Sub-Grid Scales

— Only Sub-Grid Small Scales Removed from the Dynamical Equations

— Large Numerical Calculations Involved Solving for Super-Grid Scales

— Applications to Homogeneous and Shear Flows

— Large Scale Structures are Computable in Detail

— Spectra are Computable Up to Grid-Induced Cutoff

TRANSPORT MODEL

REYNOLDS AVERAGED NAVIER-STOKES

Turbulence
Model

$l_d \approx \frac{1}{\mathrm{Re}^{3/4}} L$ $\ll$ Δ $\ll$ L

Dissipation scale | Grid Size | Large scale (eddy)

Eddy viscosity or $K - \mathcal{E}$ model
e.g., $\overline{uv} = -\nu_{\text{eddy}} \nabla \overline{U}$

Large eddies solved
by Reynolds averaged
Navier-Stokes,
e.g., $\frac{\partial \overline{U}}{\partial t} = \frac{\partial}{\partial z}(\nu + \nu_{\text{eddy}})\frac{\partial \overline{U}}{\partial z}$

Result: <u>Smooth, non-random $\overline{U}$</u>

TRANSPORT MODELS OF TURBULENCE

— Reynolds Averaged Equations of Motion

— Equations for Mean Velocity, RMS Velocity Fluctuations, ...
$\bar{U}(x,t)$ $\langle v(x,t)\, v(x,t)\rangle$

— Closures Often Based on Gradient Transport Ideas (Eddy Viscosity)

— All Small Scales Removed from the Dynamical Equations

— Applications to Shear Flows

— No Information Deduced About Small Scale Spectra, ...

ANALYTICAL ΓHEORIES OF TURBULENCE

— Multi-Point, Mul'i-Time Moments Usually Involved

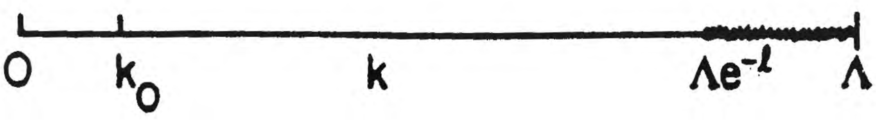
— All Scales Treated Statistically

— Renormalized Perturbation Methods Normally Used

— Currently Applied Principally to Homogeneous Turbulence

— Huge Numerical Calculations Involved for Shear Flows

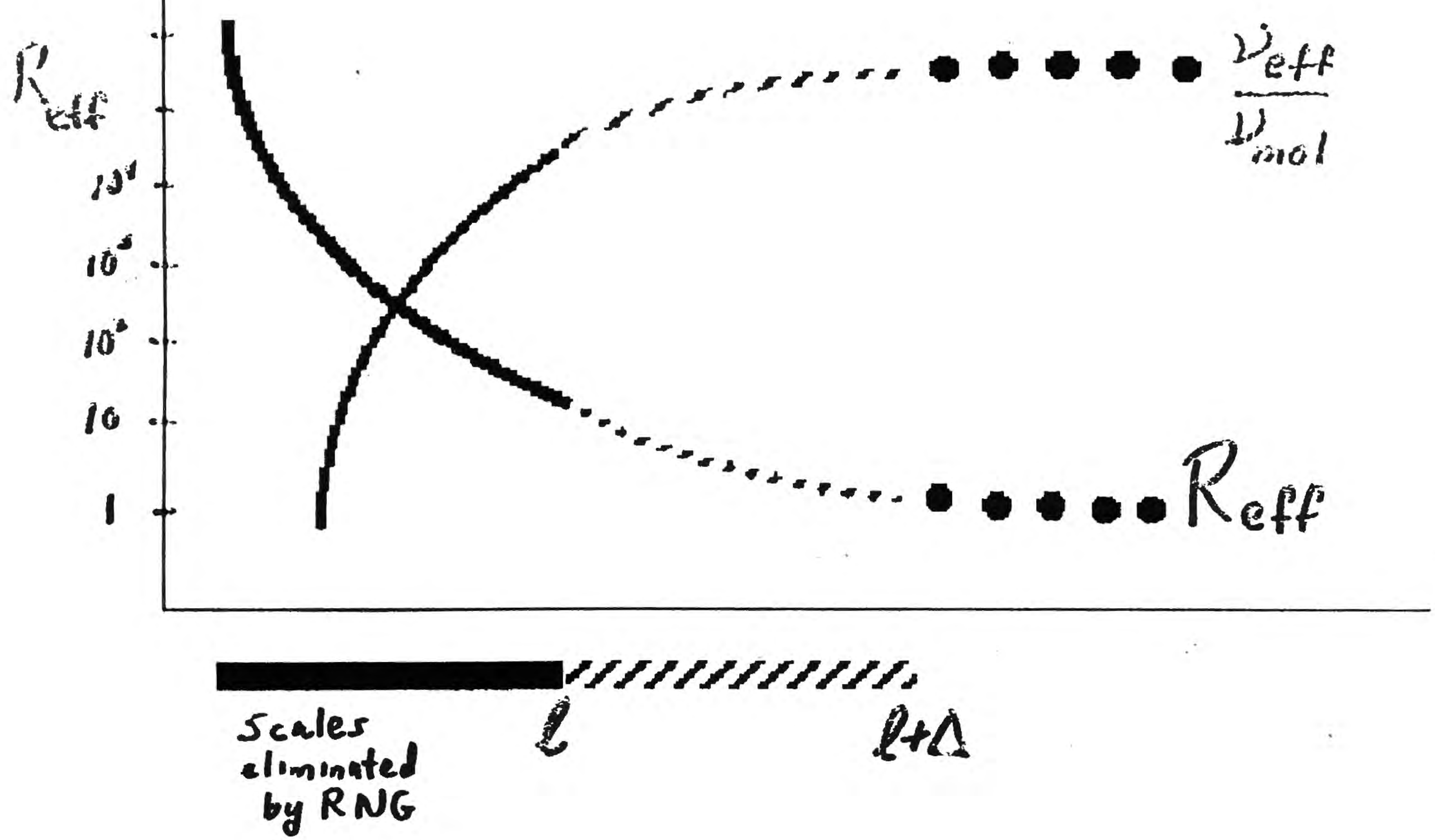
DYNAMIC RENORMALIZATION GROUP



Infrared renormalization group— long-distance behavior

1. Remove degrees of freedom
   $\Lambda e^{-\ell} < q < \Lambda$
2. Rewrite (by rescaling) Navier-Stokes equations as renormalized system for $v^{<}$ $(k < \Lambda e^{-\ell})$ with modified viscosity, force, coupling

RNG: Schematic of Mode Elimination Procedure



"The renormalization group is one of the fundamental approaches to tackling this problem of what to do when you cannot make your grid small enough to use the fundamental equation. How do you increase the grid spacing beyond the level of a straight numerical approach, yet preserve all of the reliability that working from a fundamental equation can give you?"

Kenneth Wilson (1985)

Intrinsic Stirring Force in Turbulence and the ε-Expansion

Large-scale force to model the effects of *initial* and *boundary* conditions

$$\left(-i\omega + \nu_0 k^2\right)u_\alpha(\mathrm{k},t) = -\tfrac{1}{2} i P_{\alpha\beta\gamma}(\mathrm{k})\int u_\beta(\mathrm{p},\Omega)u_\gamma(\mathrm{k}-\mathrm{p},\omega-\Omega)d\mathrm{p}d\Omega + f_\alpha(\mathrm{k},\omega)$$

$$\left\langle \mathrm{f}_\alpha(\hat{\mathrm{k}})\mathrm{f}_\beta(\hat{\mathrm{k}}')\right\rangle \propto D_0 \mathrm{P}_{\alpha\beta}(\mathrm{k})\delta(\mathrm{k})\delta(\mathrm{k}+\mathrm{k}')\delta(\omega+\omega')$$

DIFFICULTY: Nonlinear solutions of the Navier-Stokes equations involve an 'infinity' of interacting f's to produce u(k) [k finite]

Correspondence Principle (Yakhot & Orszag 1986)

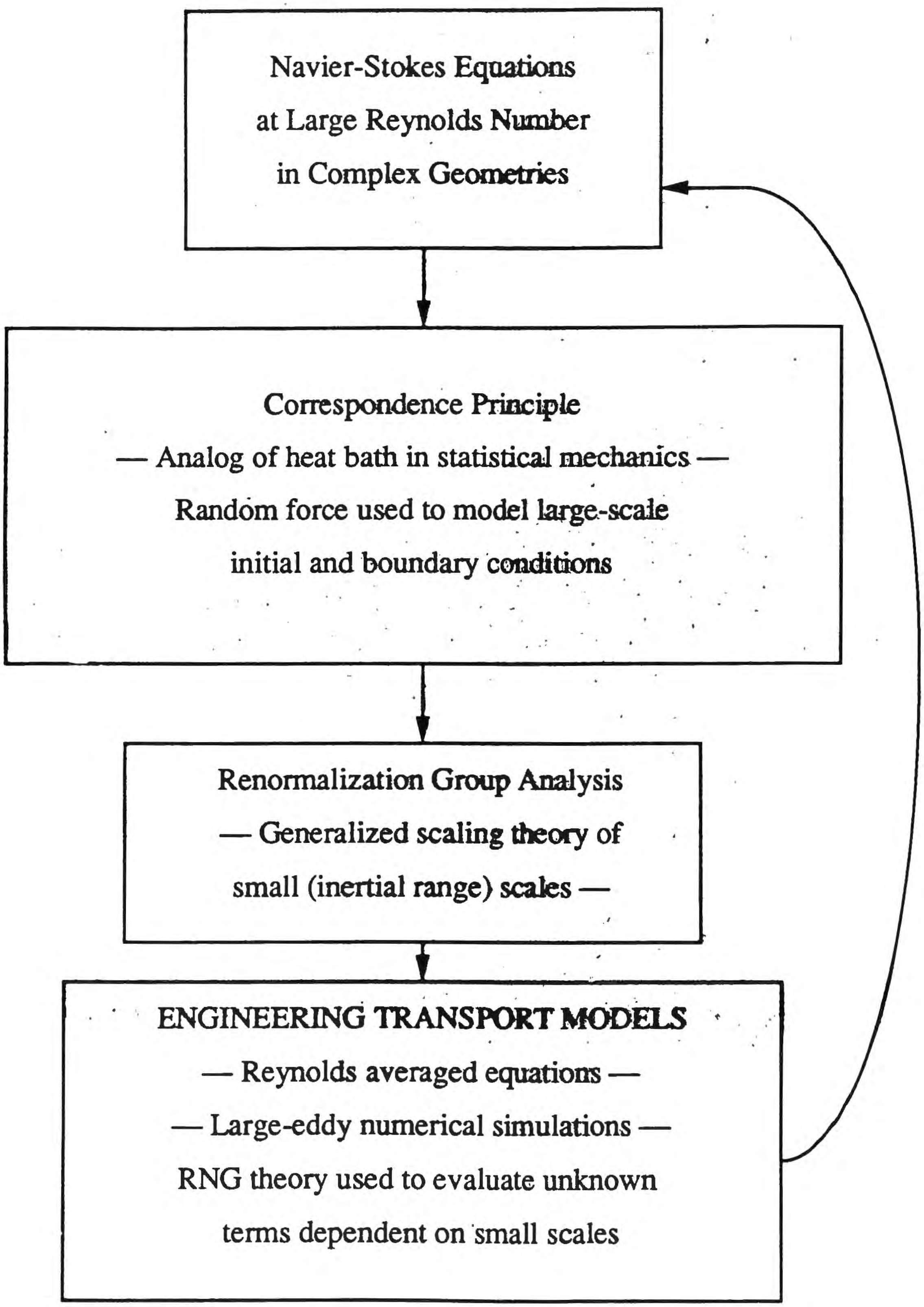
$$\left\langle \mathrm{f}_\alpha(\hat{\mathrm{k}})\mathrm{f}_\beta(\hat{\mathrm{k}}')\right\rangle \propto D_1 \mathrm{P}_{\alpha\beta}(\mathrm{k})k^{1-\varepsilon}\delta(\mathrm{k}+\mathrm{k}')\delta(\omega+\omega')$$

$$\delta(\mathbf{k}) = \lim_{\varepsilon\to 4}\frac{(4-\varepsilon)k^{1-\varepsilon}}{4\pi}$$

Gel'fand

RENORMALIZATION GROUP (RNG) THEORY

— A Practical Approach to the Turbulence Problem —



Langevin Model

$$\frac{\partial \mathrm{u}^{\ell}}{\partial t} = -\text{“}\nu(\ell)\text{”}\mathrm{u}^{\ell}\ell^{-2} + f^{\ell}$$

Nonlocal convolution operator

Assume

$$\frac{d\nu(\ell)}{d\ell} \propto \mathcal{E} \quad \text{(rate of energy dissipation)}$$

Dimensional analysis $\Longrightarrow$

$$\frac{d\nu}{d\ell} = \frac{A\mathcal{E}\ell^3}{\nu^2}, \quad \nu(\ell_d) = \nu_0$$

Solution:

$$\nu(\ell) = \nu_0 \left[1 + \frac{3}{4}\frac{A\mathcal{E}}{\nu_0^3}\left(\ell^4 - \ell_d^4\right)\right]^{1/3} \qquad (\ell > \ell_d)$$

$$\nu(\ell) \sim \left(\frac{3}{4}A\mathcal{E}\right)^{1/3} \ell^{4/3} \quad (\ell \gg \ell_d)$$

Renormalization Group Subgrid Model for LES

$$K \propto 1/\Delta$$

$$\nu_{eddy} = \nu_{mol}\left[1 + \frac{3}{4}\frac{A\mathcal{E}}{(2\pi)^4\nu_{mol}^3}\left(\Delta^4 - \eta_d^4\right)\right]^{1/3}$$

$$\mathcal{E} = \nu_{eddy}\left|\nabla\overline{U}\right|^2$$

High turbulence limit

$$\nu_{eddy} \sim \left[\frac{3}{4}\frac{A}{(2\pi)^4}\right]^{1/2} \quad \Delta^2\left|\nabla\overline{U}\right|$$

Transitional regimes

$$\nu_{eddy}^3 = \nu_{mol}^3 + \frac{3}{4}\frac{A}{(2\pi)^4}(\Delta^4 - \eta_d^4)\nu_{eddy}\left|\nabla\overline{U}\right|^2$$

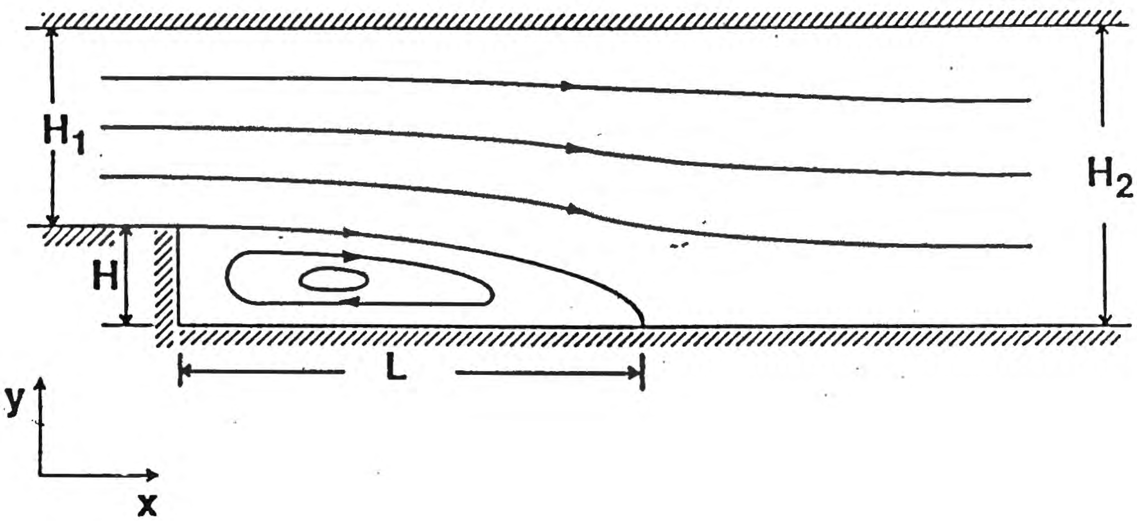
— unphysical roots can be a problem

<u>Alternate Formulation</u>

$$\mathcal{E} = \frac{S^2}{\nu_{eddy}} \qquad S = \nu_{eddy}\left|\nabla\overline{U}\right|$$

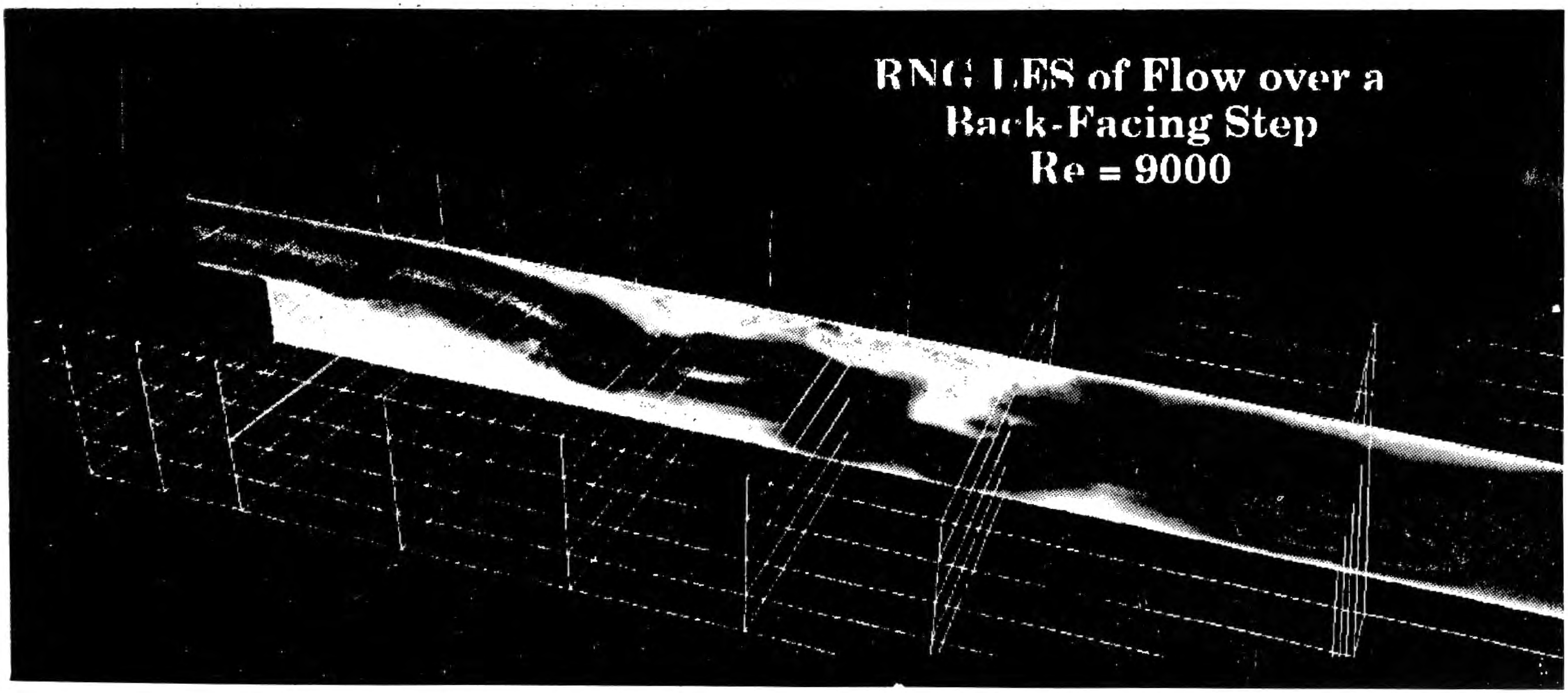
$$\nu_{eddy}^4 = \nu_{mol}^3 \quad \nu_{eddy} + \underbrace{\frac{3}{4}\frac{AS^2}{(2\pi)^4}(\Delta^4 - \eta_d^4)}_{\geq 0}$$

Only 1 real root with $\nu_{eddy} \geq \nu_{mol}$



Turbulent flow over a backward facing step

Figure 3


RNG LES of Flow over a
Back-Facing Step
Re = 9000

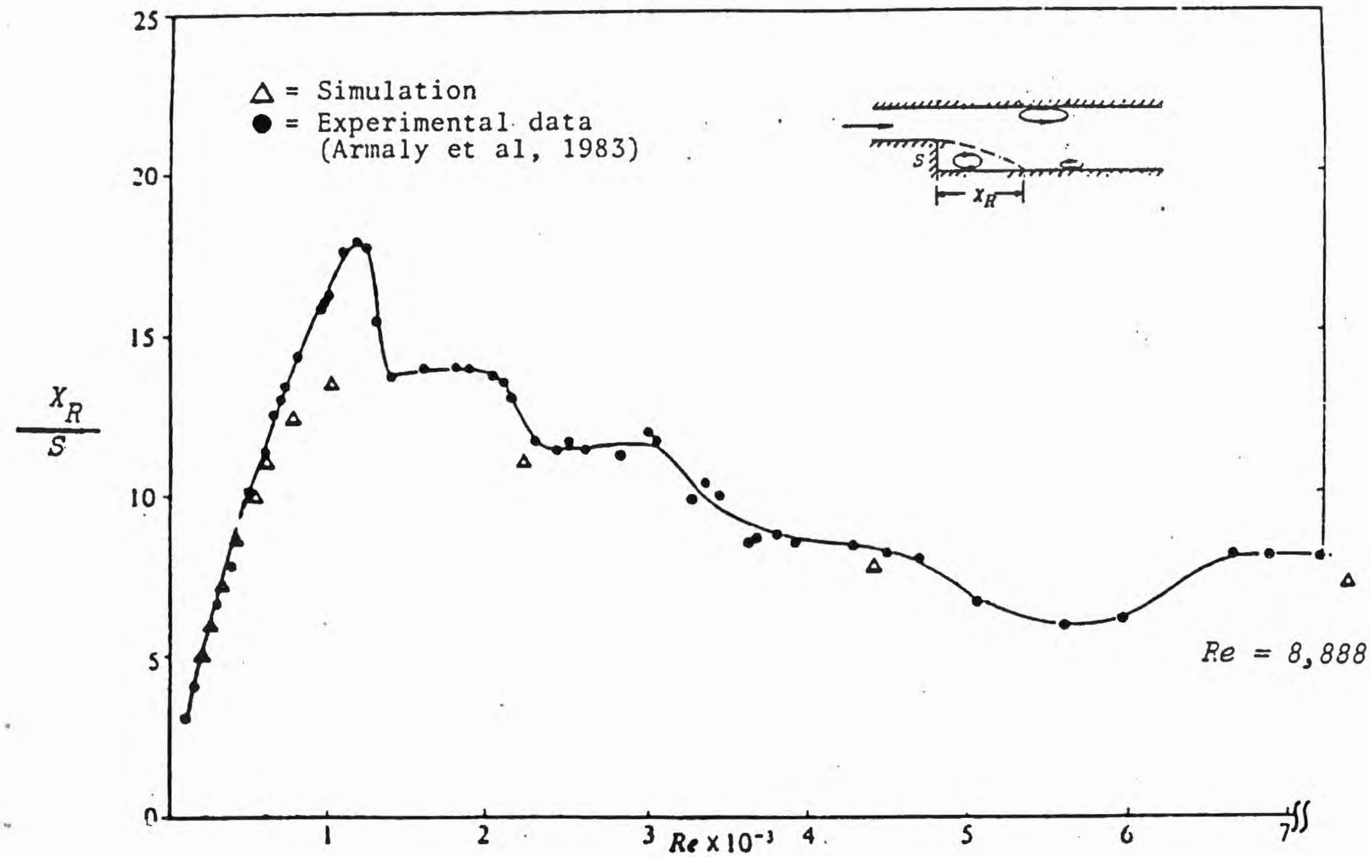


Figure 9: Normalized separation length X_R versus Reynolds number; S = step height.

Prandtl mixing length theory

$$\mathcal{E} = \nu_{eddy} \left|\nabla\overline{\mathrm{U}}\right|^2$$

$$\mathrm{k_0} = 2\pi/\mathrm{L}$$

$$\nu_{eddy} \sim \left(\frac{3}{4}\mathrm{A}\right)^{1/3} \mathcal{E}^{1/3}\mathrm{k}_0^{-4/3}$$

$$\nu_{eddy} = \left[\underbrace{\left\{\left(\frac{3}{4}\mathrm{A}\right)^{1/4} /2\pi\right\}}_{=\,0.094}\mathrm{L}\right]^2 \left|\nabla\overline{\mathrm{U}}\right|$$

Eddy Viscosity:

$$\nu = \nu_0(1 + H(\frac{a\Delta^4}{\nu_0^3}\overline{\varepsilon} - C))^{1/3}, \tag{1}$$

$$\overline{\varepsilon} = \nu(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i})^2 + \beta U_i \frac{\partial p}{\partial x_i} \tag{2}$$

Length Scale (Δ):

$$\Delta = y_+ \ \ if \ \ y_+ < \lambda, \ \ and \ = \lambda \ otherwise, \tag{3}$$

where

$$\lambda = \gamma(1 - \frac{\theta}{\delta_*})^{-1}\delta_* \tag{4}$$

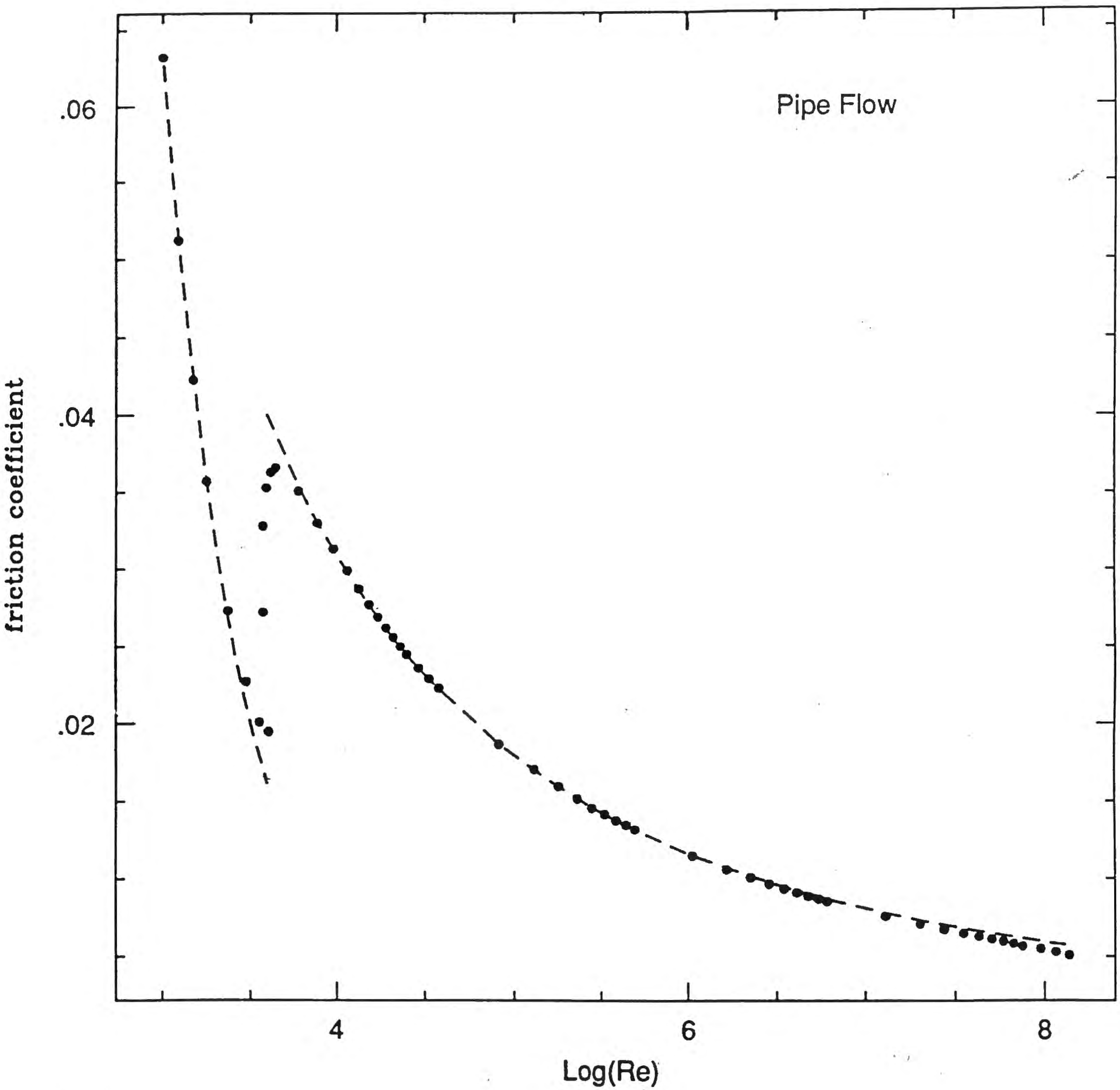
δ_* - **di-placement thickness**
θ - **momentum-loss thickness**
δ_*/θ - **shape factor**

Pressure Gradient Term ($\beta U_i \partial p/\partial x_i$):

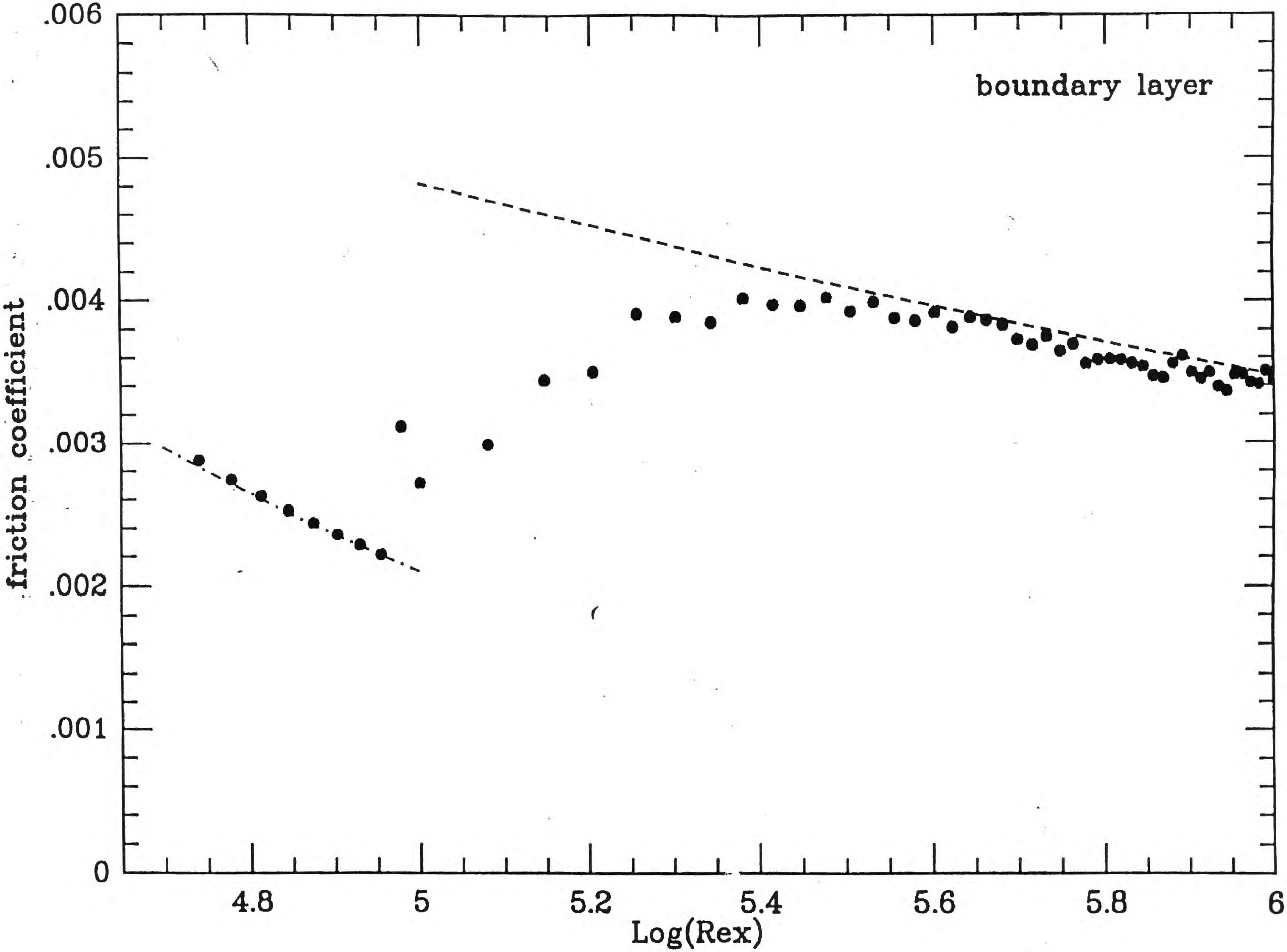
$$\beta = \beta_1(1. - exp(-\beta_2(y_+ - \Delta)/\lambda)) \tag{5}$$

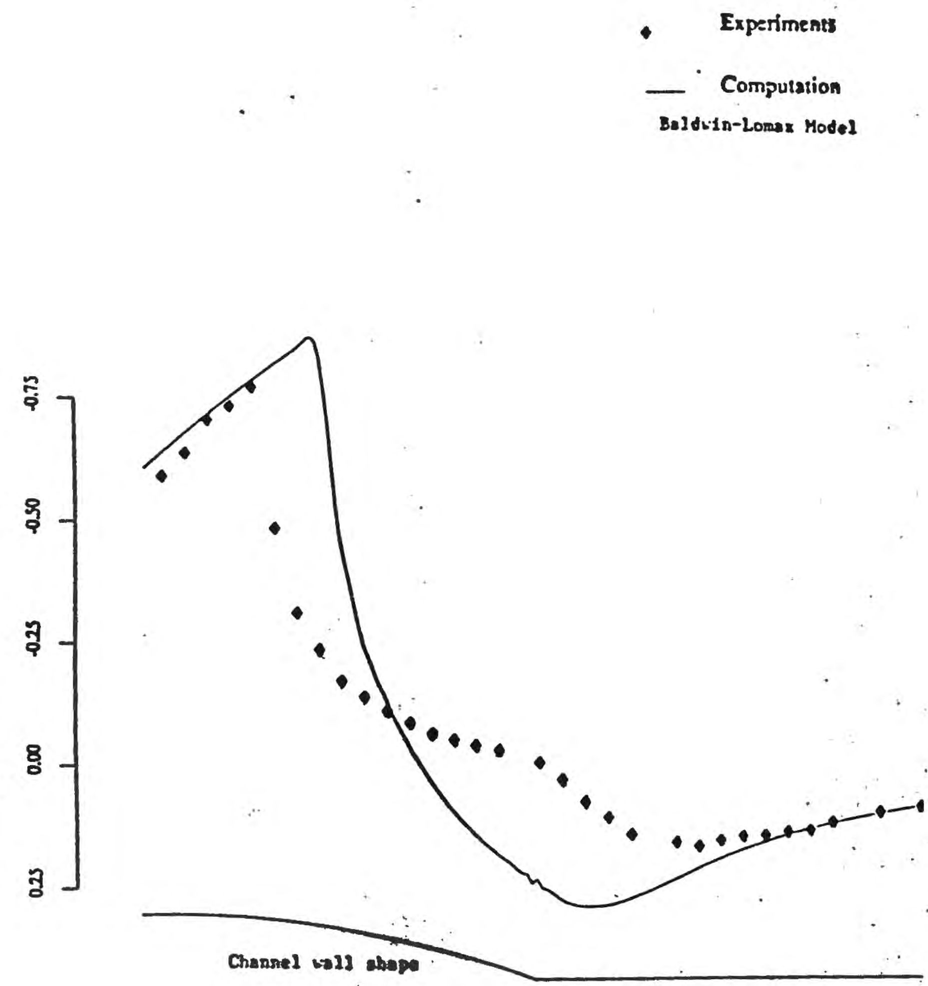
Constants:

$a = 0.0256$
$C \approx 100$
$\gamma = 0.28$
$\beta_1 = 5.$
$\beta_2 = 0.12$

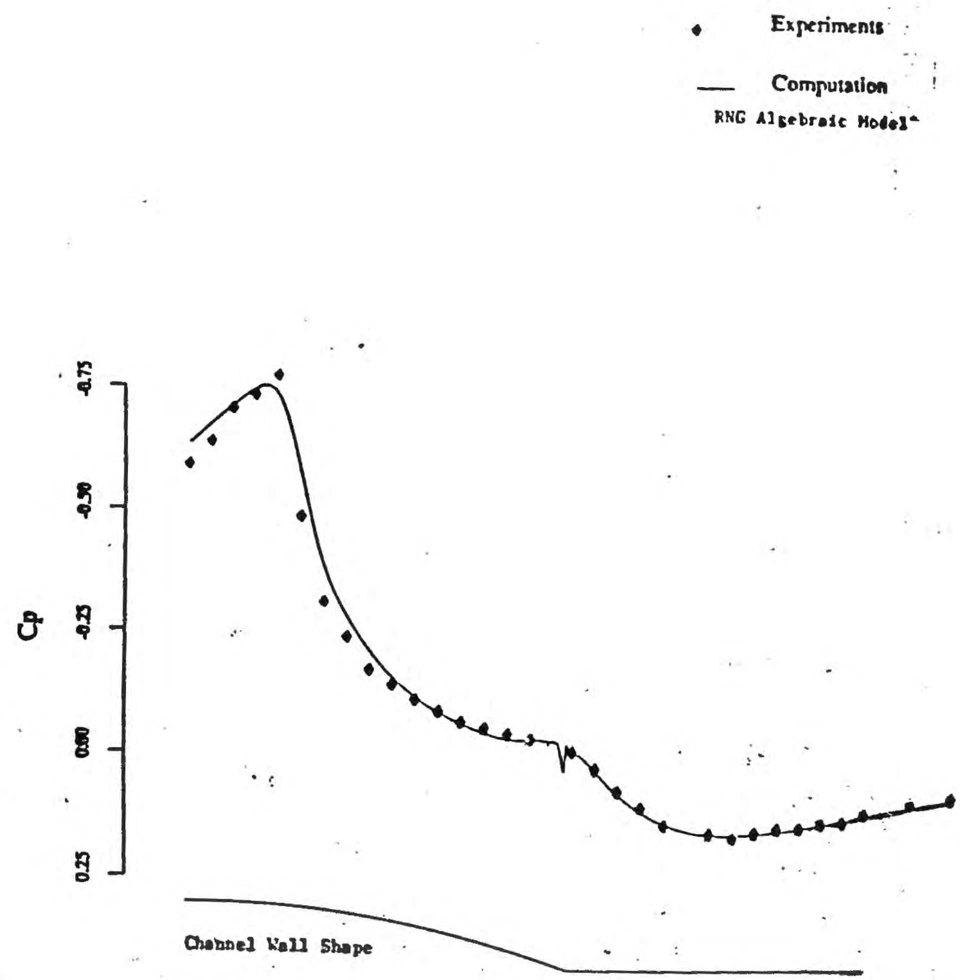


Pipe Flow
.06
.04
.02
friction coefficient
4
6
8
Log(Re)


boundary layer
friction coefficient
Log(Rex)
.006
.005
.004
.003
.002
.001
0
4.8
5
5.2
5.4
5.6
5.8
6



ARC BAL & LOMAX
MACH 0.675 ALPHA 0.000
CL -0.0901 CD 0.0156 CM 0.4685
GRID 320X64 NCYC 200 RES0.000E+00

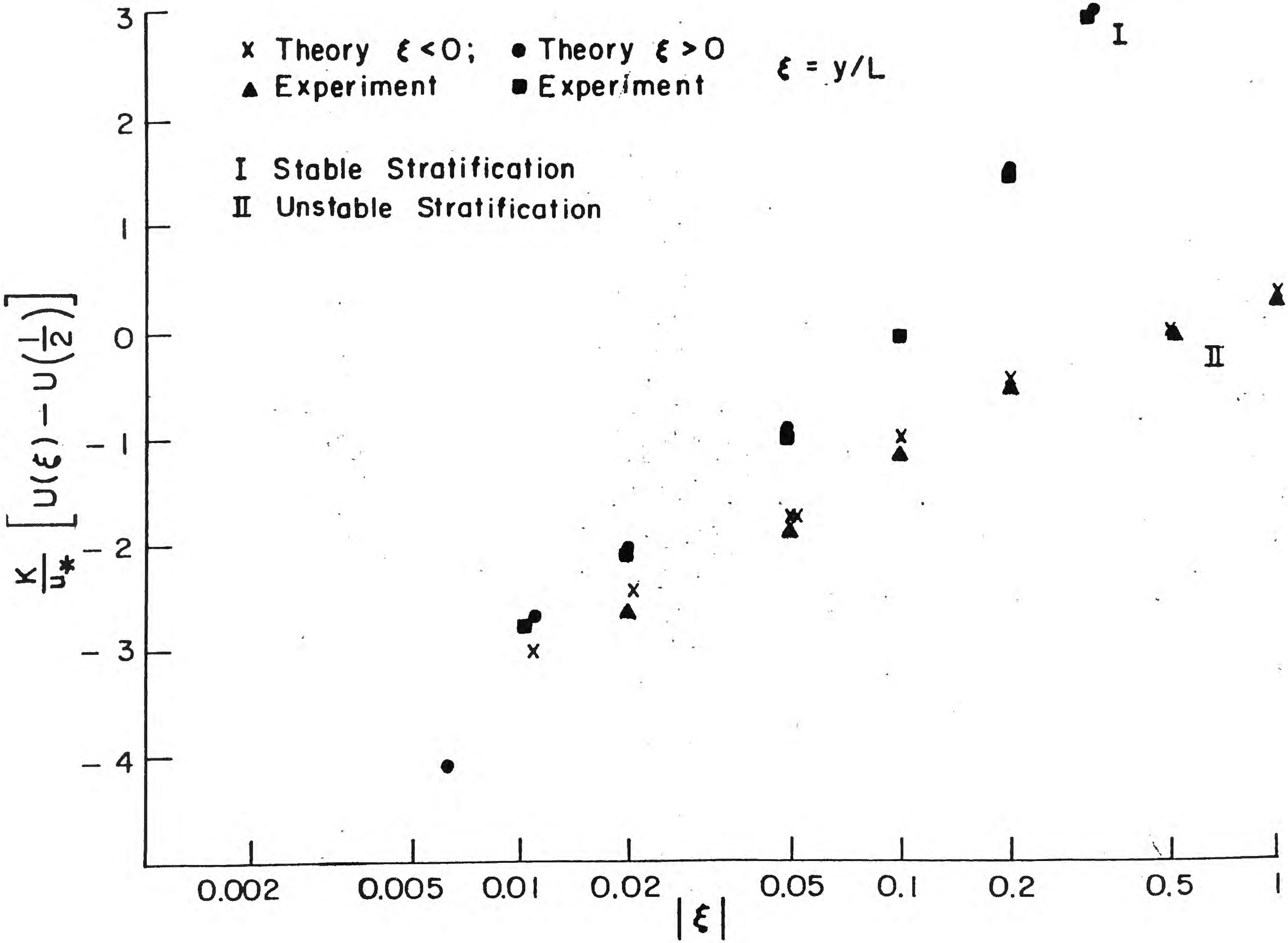


ARC
MACH 0.675 ALPHA 0.000
CL -0.0241 CD 0.0162 CM 0.1344
GRID 320X64 NCYC 100 RES0.000E+00

Example: Stratified Shear Flow

$$\nu_{eddy} = \nu_0 \left[1 + \frac{3}{4} \frac{A}{\nu_0^3} \left(\mathcal{E} - g \frac{\partial \overline{T}}{\partial z} \right) \left(\ell^4 - \ell_d^4 \right) \right]^{1/3}$$

RNG CLOSURE FOR STRATIFIED TURBULENCE



2-40

APPLICATION OF RG TO TURBULENCE MODELLING

RG Length Scale Model for High Mach Flows

$$\mathcal{K} = \frac{3}{2}\mathcal{E}^{2/3}\mathrm{k}^{-2/3} \lesssim \gamma^2 \mathrm{c}^2 \left[\mathrm{V}^2 < \gamma^2\mathrm{c}^2 \text{ or else eddy shoclets form}\right]$$

so

$$\nu_{eddy} = \left(\frac{3}{4}\mathrm{A}\right)^{1/3} \mathcal{E}^{1/3}\mathrm{k}_0^{-4/3} \lesssim \frac{\mathrm{c}^4}{\mathcal{E}} \simeq \frac{\mathrm{c}^4}{\nu_{eddy}}\left|\nabla\overline{\mathrm{U}}\right|^2$$

so

$$\nu_{eddy} \lesssim \frac{\mathrm{c}^2}{\left|\nabla\overline{\mathrm{U}}\right|} \quad \left(\text{not } \nu_{eddy} \propto \left|\nabla\overline{\mathrm{U}}\right| \text{ (Prandtl)}\right)$$

Self–Focusing of High Ma Jet/Wake Flows

RNG K-$\mathcal{E}$ Eddy Viscosity

High Turbulence Formulation

$$\nu(\ell) \sim \left(\frac{3}{4}\mathrm{A}\mathcal{E}\right)^{1/3} \ell^{4/3}$$

$$\mathrm{K} = \int_{\ell^{-1}}^{\infty} \mathrm{C}_{\mathrm{K}O}\mathcal{E}^{2/3}\mathrm{k}^{-5/3}\mathrm{dk} = \frac{3}{2}\mathrm{C}_{\mathrm{K}O}\mathcal{E}^{2/3}\ell^{2/3}$$

$$\nu = \frac{(\frac{3}{4}\mathrm{A})^{1/3}}{(\frac{3}{3}\mathrm{C}_{\mathrm{K}O})^2} \quad \frac{\mathrm{K}^2}{\mathcal{E}}$$

$$C_\mu = \frac{(\frac{3}{4}\mathrm{A})^{1/3}}{(\frac{3}{2}\mathrm{C}_{\mathrm{K}O})^2} \overset{\mathrm{RNG}}{=} 0.0845$$

General Foundation

$$\nu = \mathrm{C}_\mu \mathrm{K}^2/\mathcal{E} \quad \text{only if} \quad \nu \gg \nu_0$$

$$\nu \quad = \quad \nu_0 \left[1 + \sqrt{\frac{\mathrm{c}_\mu}{\nu_0}} \quad \frac{\mathrm{K}}{\sqrt{\mathcal{E}}}\right]^2 \quad (\nu \geq \nu_0)$$

Renormalization Group (RNG) K-$\mathcal{E}$ Models

K = turbulent kinetic energy $K(\vec{x},t) = \frac{3}{2} V_{rms}^2$

$\mathcal{E}$ = turbulent dissipation $\mathcal{E} = \nu \, |\nabla v|^2$

$$\frac{D\vec{U}}{Dt} = \cdots$$

$$\frac{DK}{Dt} = \cdots$$

$$\frac{D\mathcal{E}}{Dt} = \cdots$$

RNG <u>Theory</u> vs Standard Model (Empirical)

- High Reynolds # constants evaluated by theory
- Rate of strain term - important for
  non-equilibrium effects and rapid distortion limit
- Low Reynolds # modifications given by RNG theo
  - No wall functions
- Boundary conditions
- Stratification + rotation effects accounted fo

RNG K-$\mathcal{E}$ Model with Finite Rate-of-Strain Effects

V. Yakhot, S. Thangam, T. B. Gatski,
S. A. Orszag, C. G. Speziale, L. M. Smith

$$\frac{\partial U_i}{\partial t} + \mathbf{U} \cdot \nabla U_i = -\nabla_i p + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right]$$

$$\frac{\partial \overline{K}}{\partial t} + \mathbf{U} \cdot \nabla \overline{K} = -\overline{\mathcal{E}} - \overline{\tau}_{ij} S_{ij} + \frac{\partial}{\partial x_i}\left(\alpha_K \nu \frac{\partial K}{\partial x_i}\right)$$

$$\frac{\partial \overline{\mathcal{E}}}{\partial t} + \mathbf{U} \cdot \nabla \overline{\mathcal{E}} = -C_{\varepsilon_1} \frac{\overline{\mathcal{E}}}{\overline{K}} \overline{\tau}_{ij} S_{ij} - C_{\varepsilon_2} \frac{\overline{\mathcal{E}}^2}{\overline{K}} - \mathcal{R} + \frac{\partial}{\partial x_i}\left(\alpha_\varepsilon \nu \frac{\partial \mathcal{E}}{\partial x_i}\right)$$

$$C_{\varepsilon_1} = 1.42, \quad C_{\varepsilon_2} = 1.68, \quad C_\mu = 0.0845, \quad \alpha_K = \alpha_\varepsilon = 1.39$$

$$\mathcal{R} = 2\nu_0 S_{ij} \overline{\frac{\partial u_\ell}{\partial x_i} \frac{\partial u_\ell}{\partial x_j}}$$

Padé Approximation to Expansion of $\mathcal{R}$ in Powers of

$$\eta = \frac{S\overline{K}}{\overline{\mathcal{E}}}$$

$$\mathcal{R} = \frac{C_\mu \eta^3 (1 - \eta/\eta_0)}{1 + \beta\eta^3} \frac{\overline{\mathcal{E}}^2}{\overline{K}}$$

Evaluation of $\Re$

- Consistency with weakly sheared turbulence $\eta \longrightarrow 0$

$$\Re \sim \nu S^3$$

- Consistency with strongly sheared (rapid distortion) turbulence

$$\Re = O(\eta) \quad \eta \longrightarrow \infty$$

Padé Approximant

$$\frac{\Re = \nu_T S^3 (1 - \eta/\eta_0)}{1 + \beta\eta^3}$$

($\Sigma r_n \eta^n$ is a geometrical series)

$$\Re = \frac{C_\mu \eta^3 (1 - \eta/\eta_0)}{1 + \beta\eta^3} \quad \frac{\overline{\mathcal{E}}^2}{K}$$

RNG FORMULATION OF K-ε TURBULENCE MODEL

$$\partial\varepsilon/\partial t + U_k \partial\varepsilon/\partial x_k = a\partial U_j/\partial x_k <u_j u_k> - Y + \partial/\partial x_k\, \alpha_\varepsilon \nu\, \partial\varepsilon/\partial x_k$$

$$\partial k/\partial t + U_k \partial k/\partial x_k = \partial U_j/\partial x_k <u_j u_k> - \varepsilon + \partial/\partial x_k\, \alpha_k \nu\, \partial k/\partial x_k$$

$$d(a/\sqrt{\varepsilon}) = -0.2176\, dv/Y_1$$

$$d(Y/\sqrt{\varepsilon^3}) = -0.3089\, dv/Y_1$$

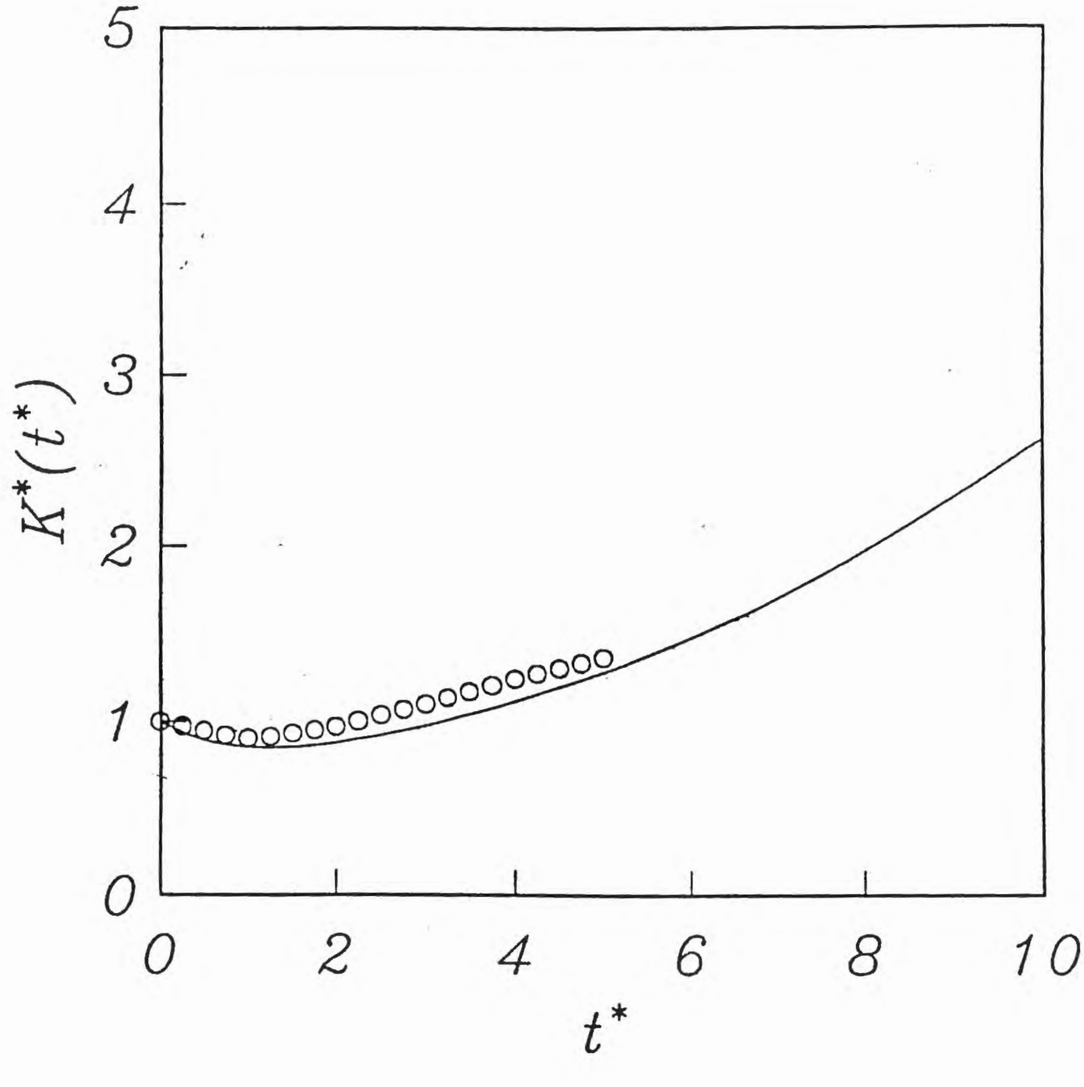
$$d(k/\sqrt{\varepsilon}) = 1.63\, vdv/Y_1$$

$$Y_1 = [(v/v_0)^3 - 1 + C]^{1/2}$$

$$|(\alpha_k - 1.3930)/0.3930|^{0.6321}$$

- $|(\alpha_k + 2.3930)/3.3930|^{0.3679} = v_0/v_R$

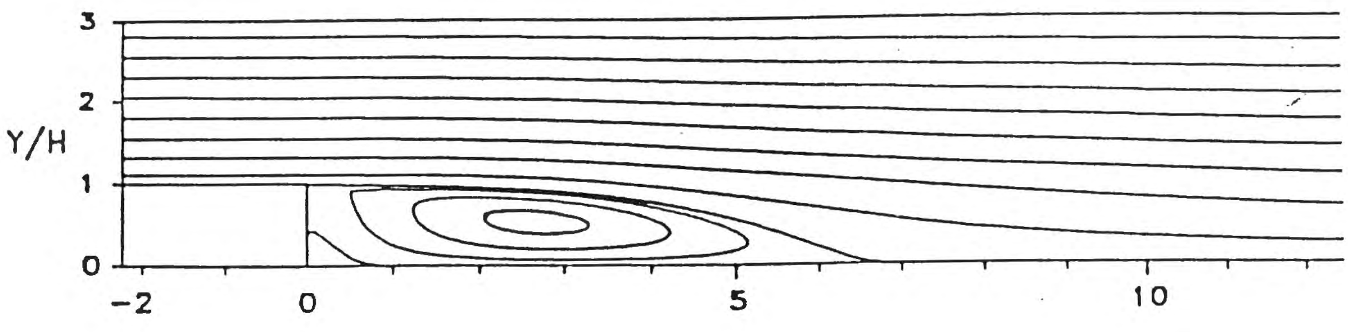
$\alpha_\varepsilon = \alpha_k$



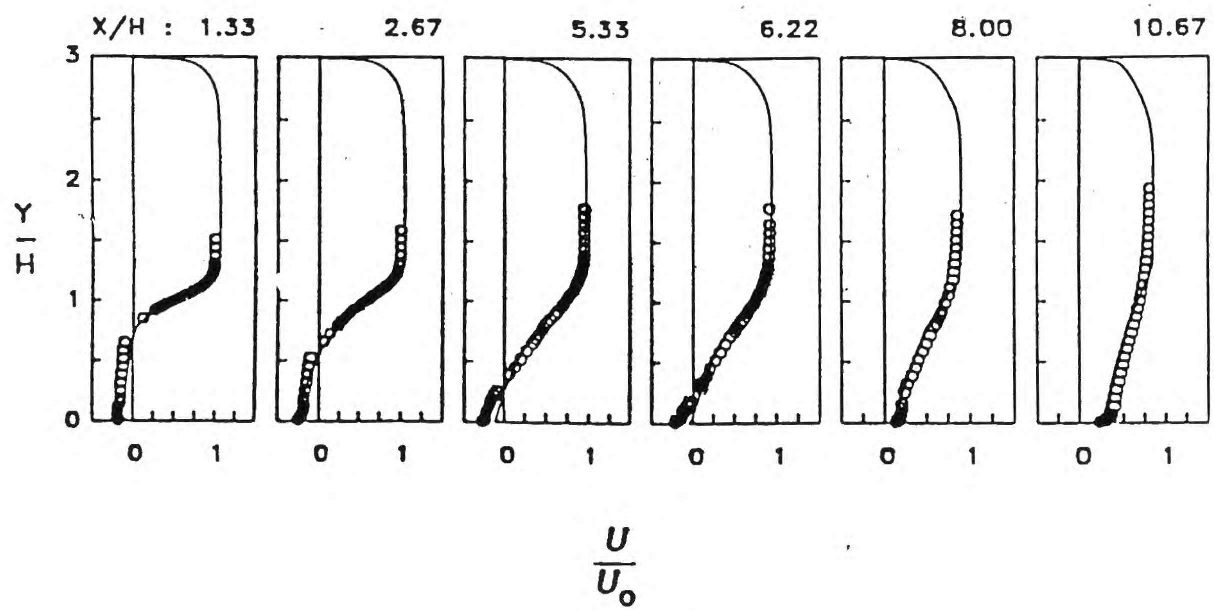
Time evolution of the turbulent kinetic energy in homogeneous shear flow.
——Relaxation model; o Large-eddy simulation of Bardina *et al*[14] for $\varepsilon_0/SK_0 = 0.296$

Figure 2

BACKWARD-FACING STEP:



(a) Streamlines



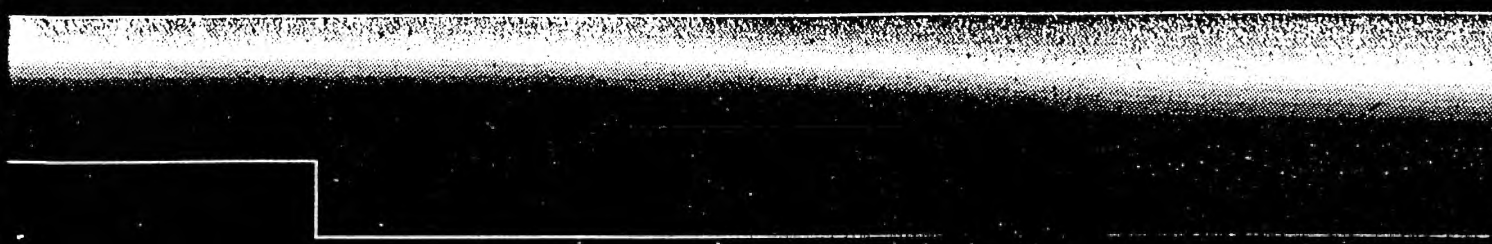
(b) Dimensionless mean velocity profile

(—— Computations with isotropic eddy viscosity;
o Experiments of Kim *et al*, 1980; Eaton & Johnston, 1981)

Computed mean flowfield for the new RNG K-ε model
[E = 1:3; Re = 132,000; 200x100 mesh]

Figure 4

FIGURE 10. Aluminum-powder pictures of streamlines over a step. Exposure time 0.5 (upper) and 5 seconds (lower).



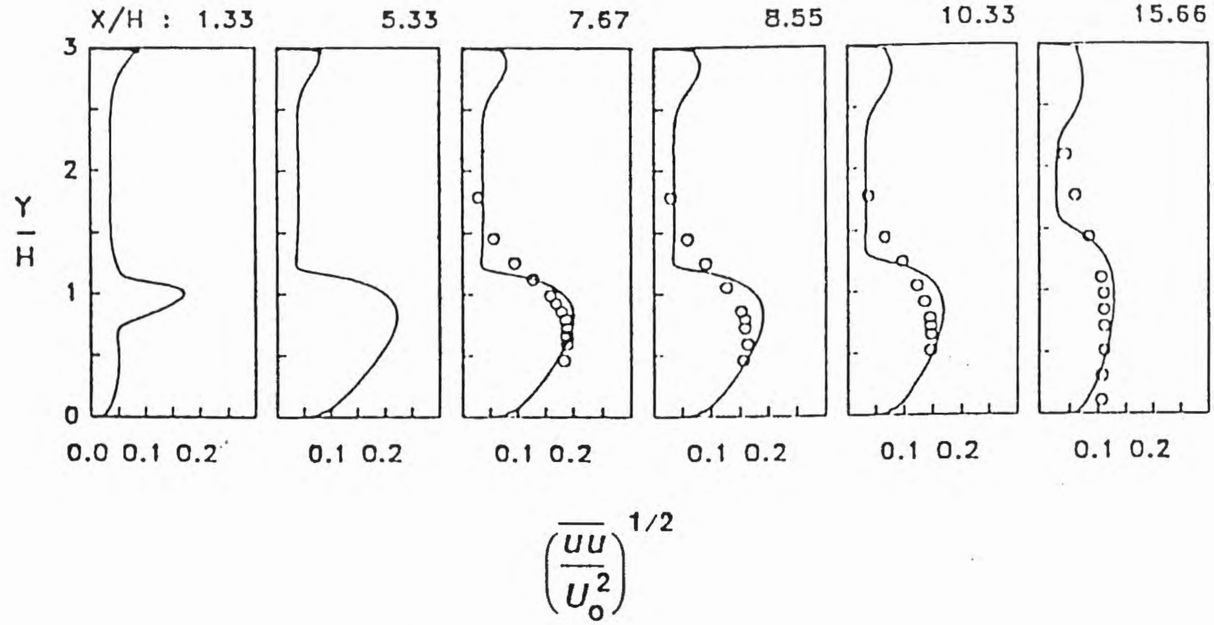
(a) Reattachment at X,H = [illegible]

(b) Primary recirculation zone

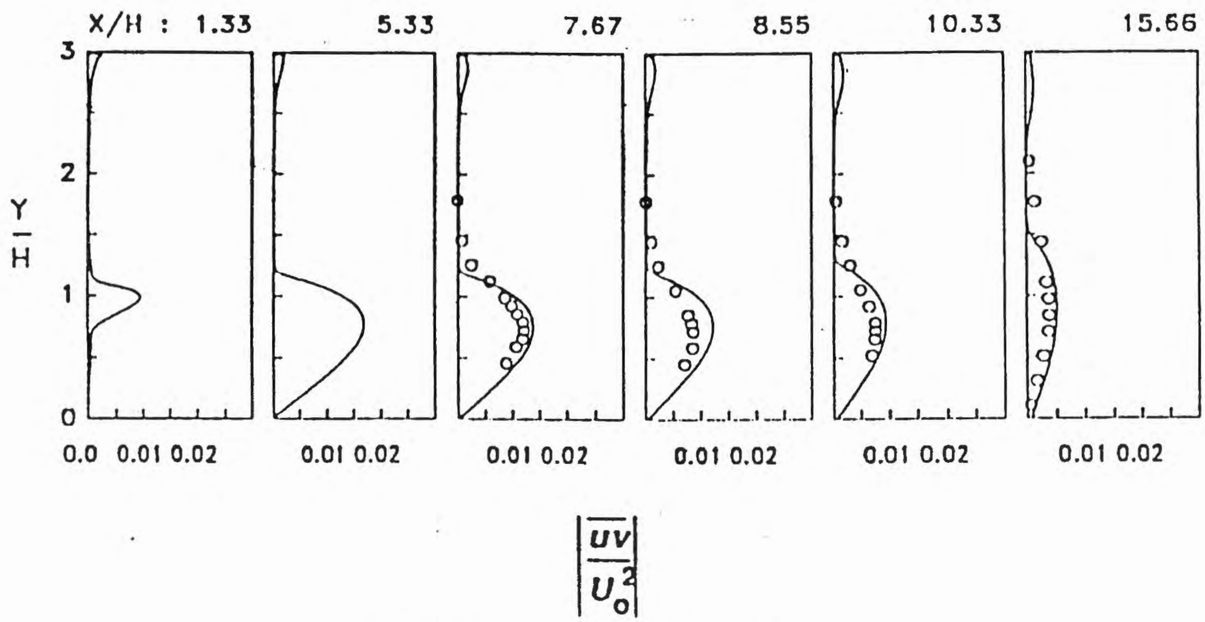
(a) Corner eddy

Streamlines for the flow over a backward facing step computed using the RNG K−ε model (Re = 88000, E=2:3)

BACKWARD-FACING STEP:



(a) Turbulence Intensity

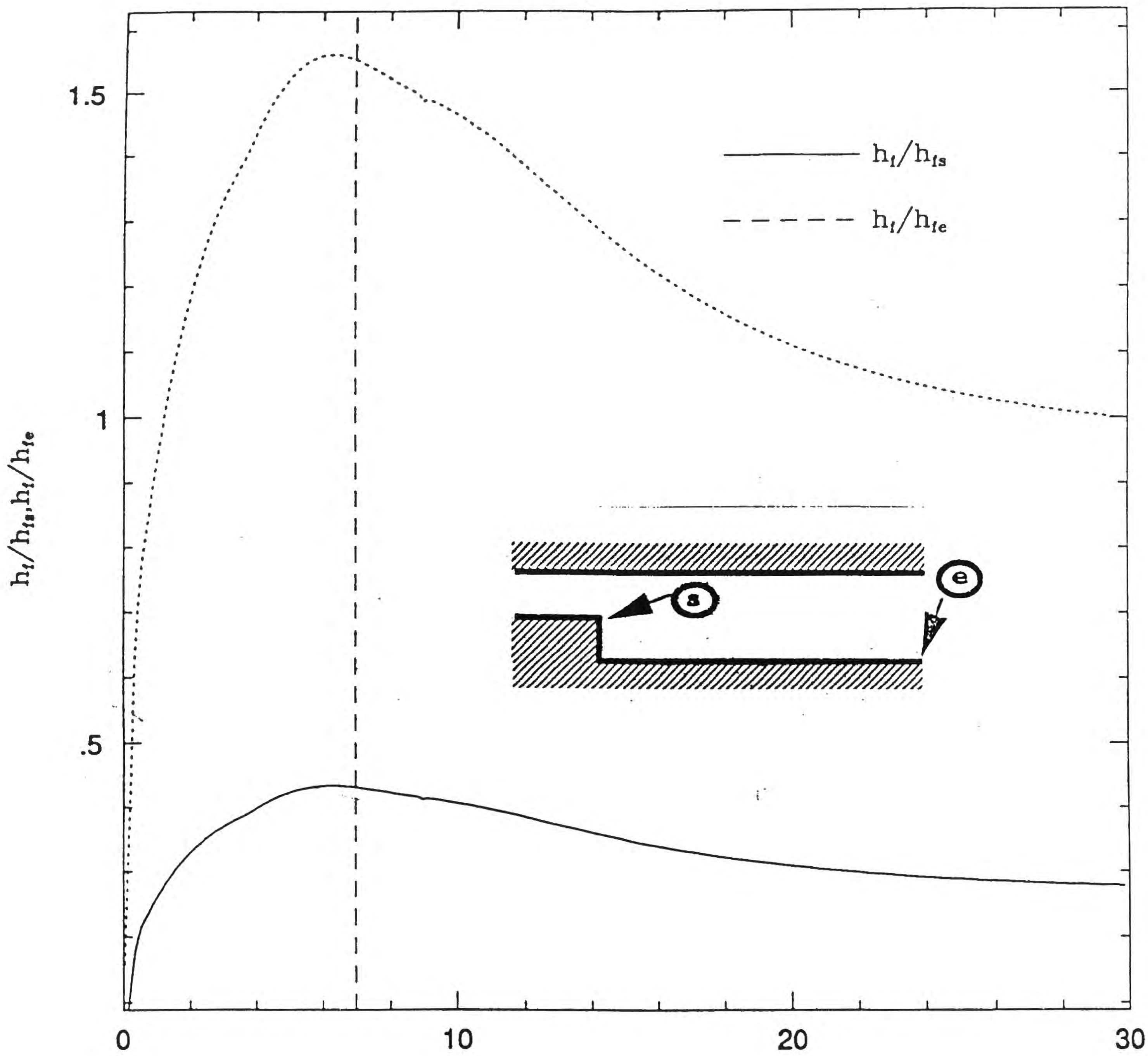


(b) Turbulence shear stress

Computed turbulence stresses for the new RNG K-ε model [E=1:3; Re = 132,000; 200x100 mesh; ——— computations with anisotropic eddy viscosity; o experiments of Kim *et al*, 1980; Eaton & Johnston, 1981]

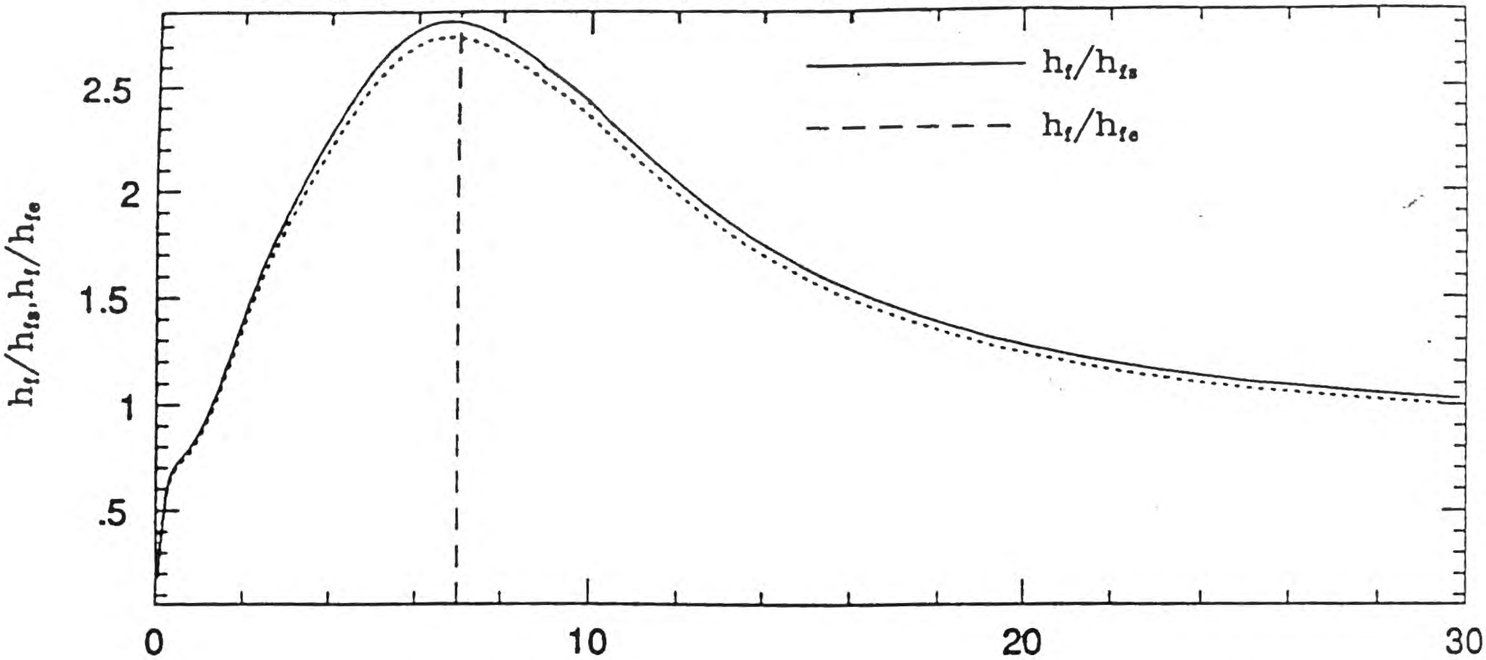
Figure 7

RNG K−ε model with RNG heat transfer for air, σ_0 = 0.7)

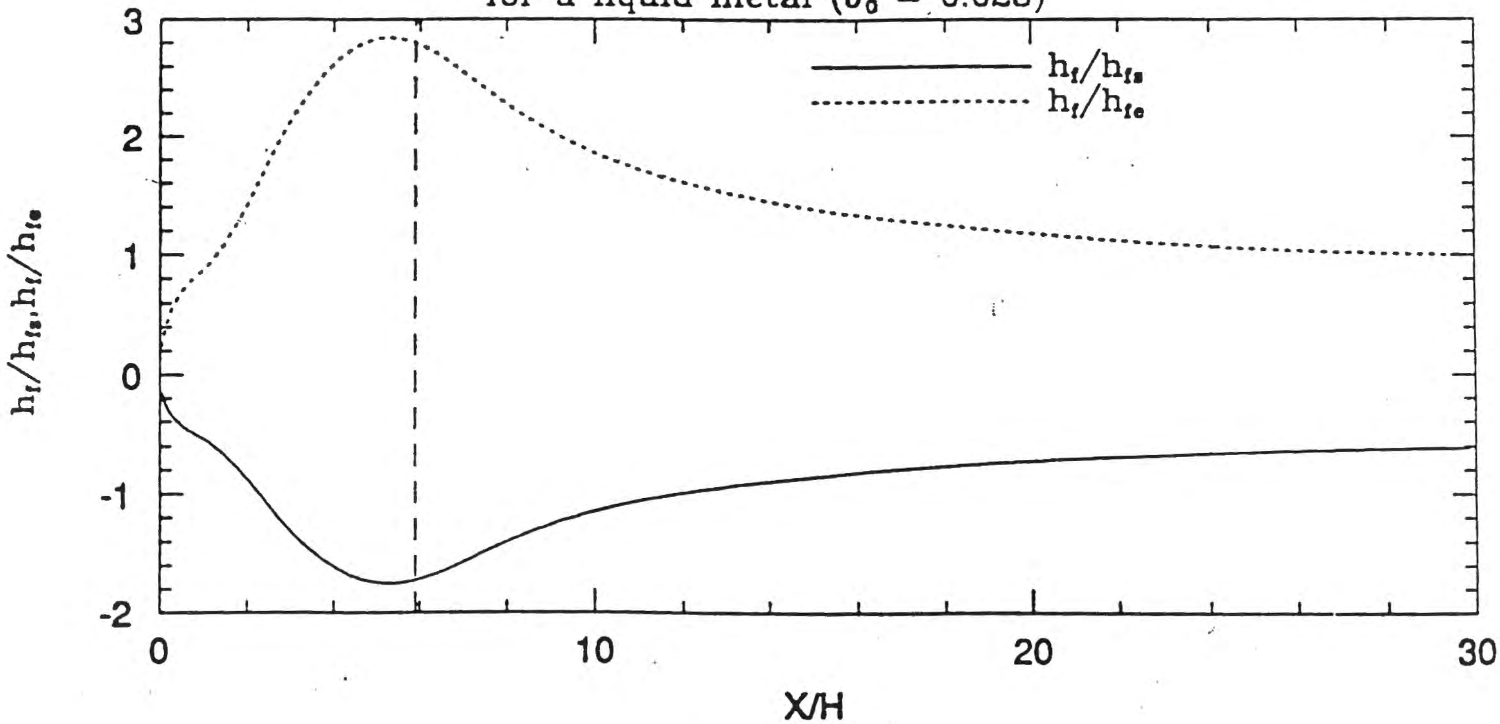


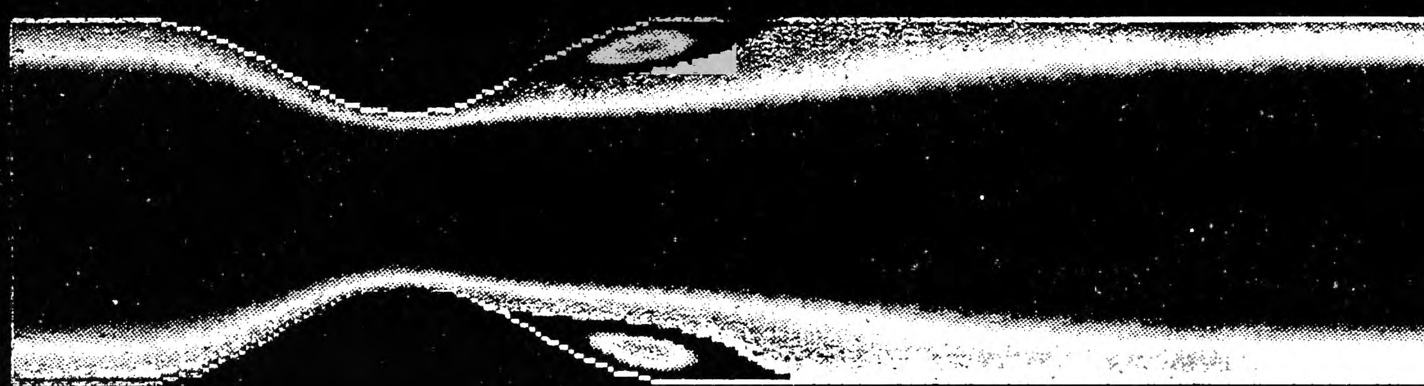
Heatflux ratios for the air flow over a backward facing step computed using the RNG K-ϵ model, Re = 88,000, E = 2:3, σ = 0.7. (h_{fs} = heat flux at the step corner, h_{fe} = heat flux at the exit)

RNG K−ε model with RNG heat transfer (liquid metal, σ_0 = 0.025)



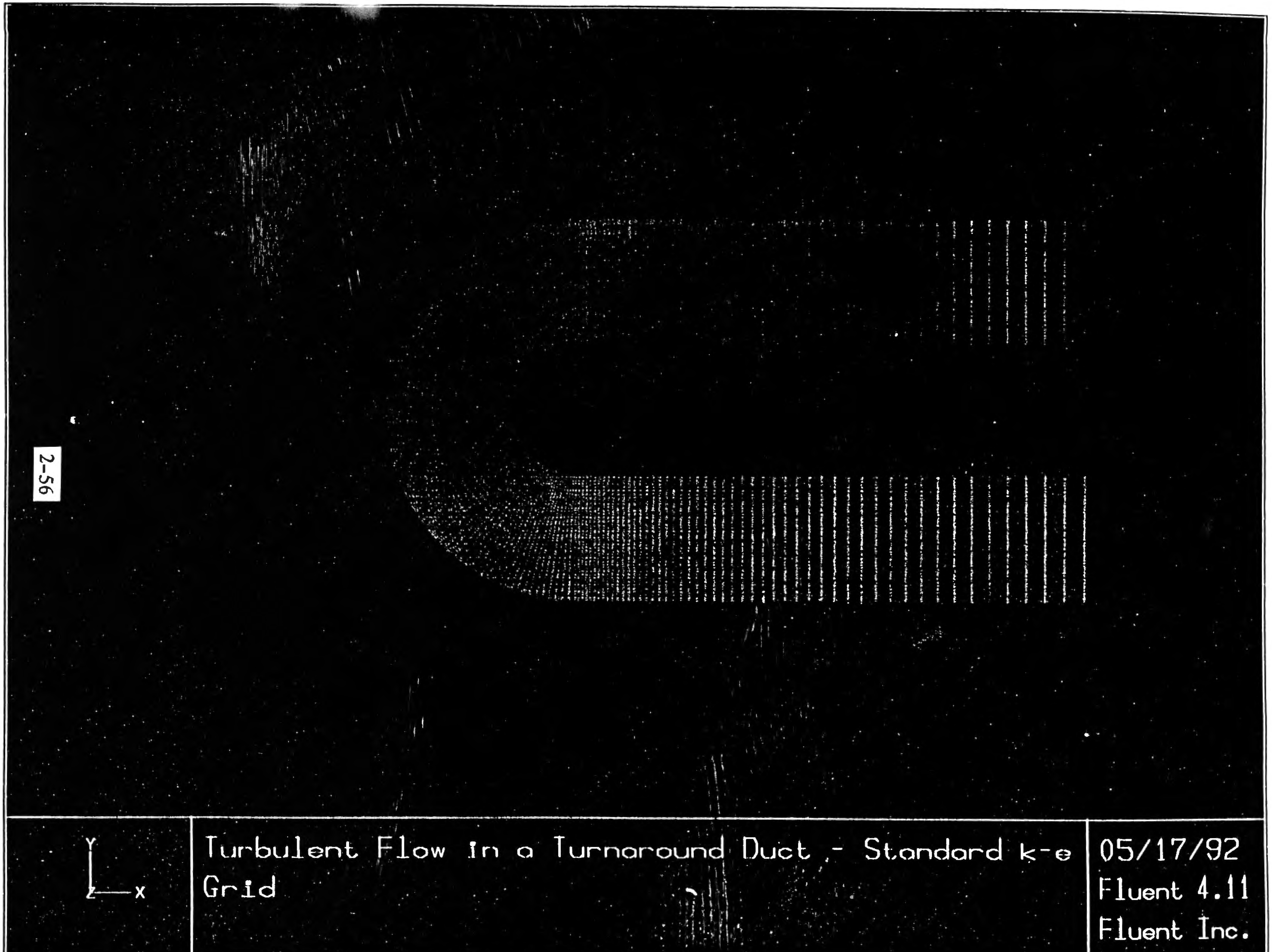
Standard K−ε model with standard heat transfer for a liquid metal (σ_0 = 0.025)

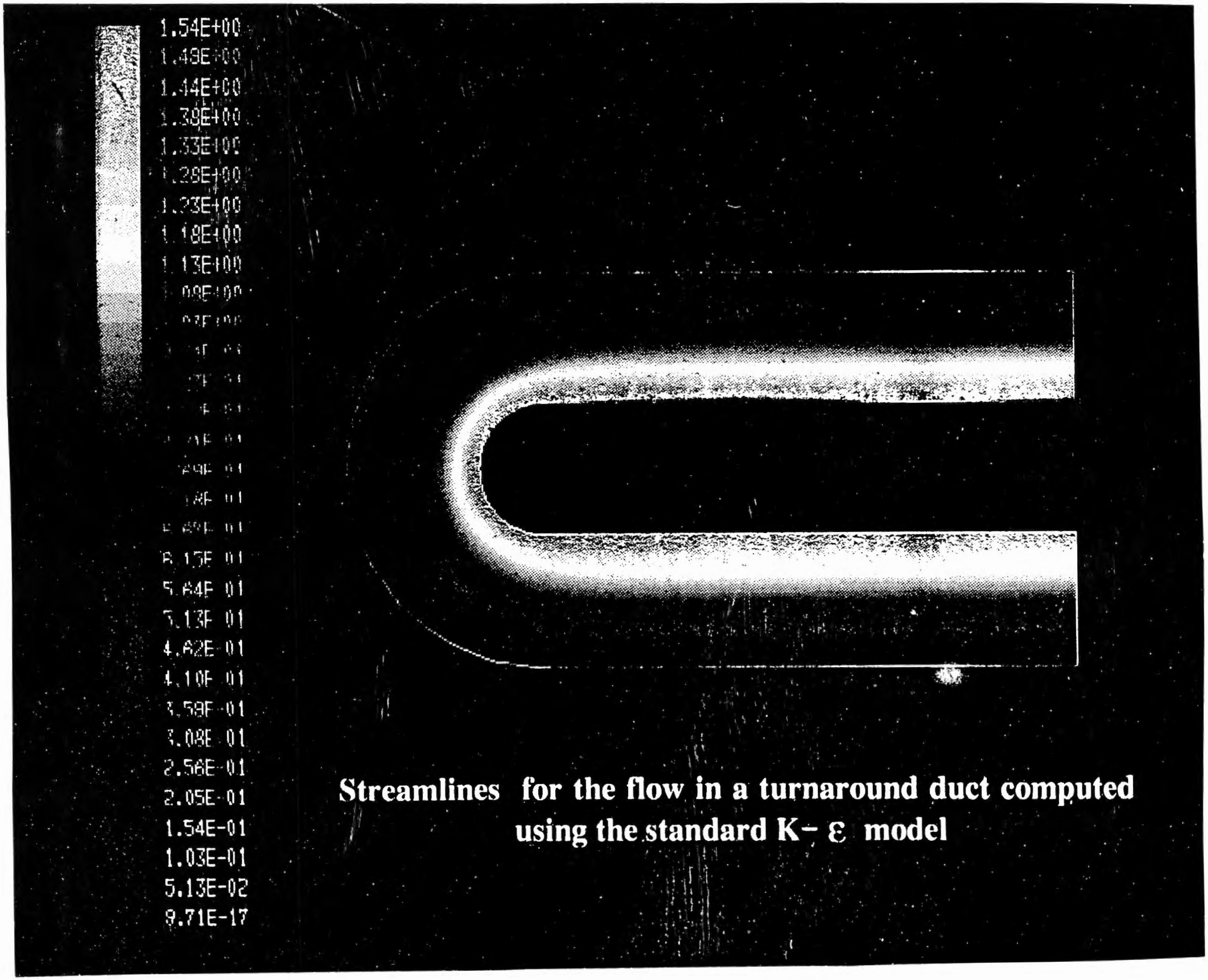




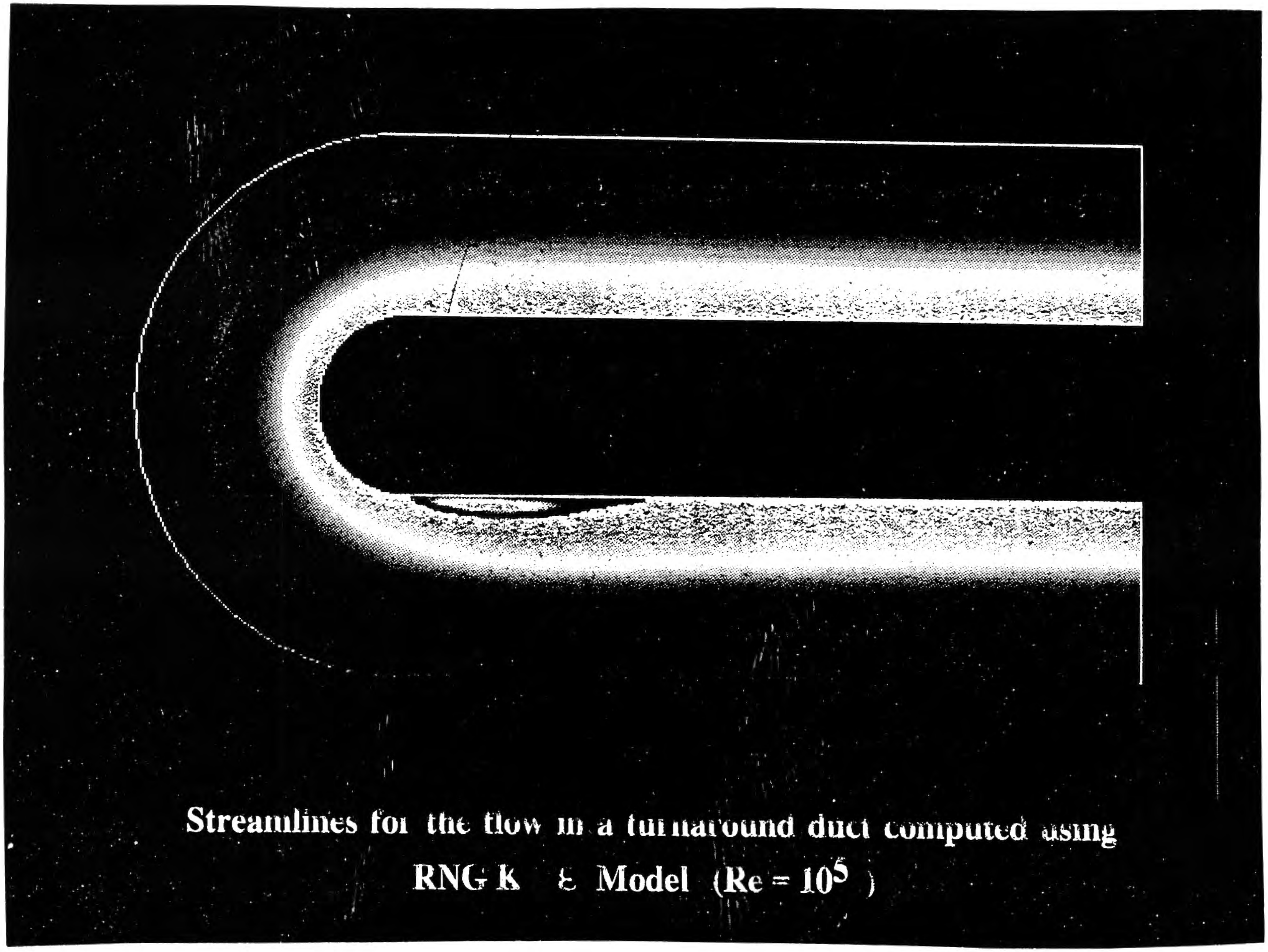
Streamlines for the flow in a constricted pipe computed using the standard K– ε model (Re = 10,000, D_{throat} / D_{in} = 0.5)

Streamlines for the flow in a constricted pipe at computed using the RNG $K-\varepsilon$ Model ($Re = 10{,}000$, $D_{throat} / D_{in} = 0.5$)

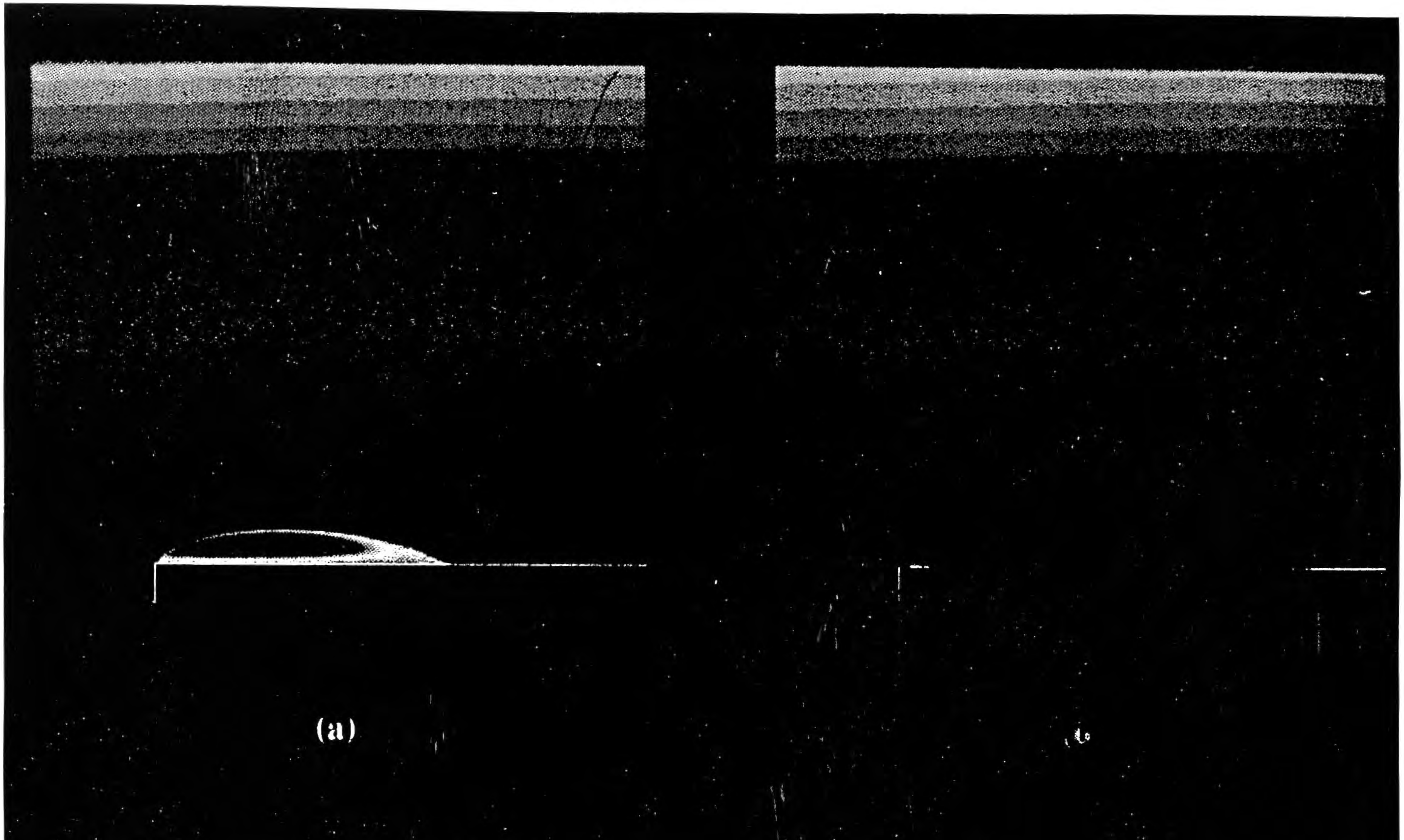

Y
Z
X
Turbulent Flow in a Turnaround Duct - Standard k-e
Grid
05/17/92
Fluent 4.11
Fluent Inc.



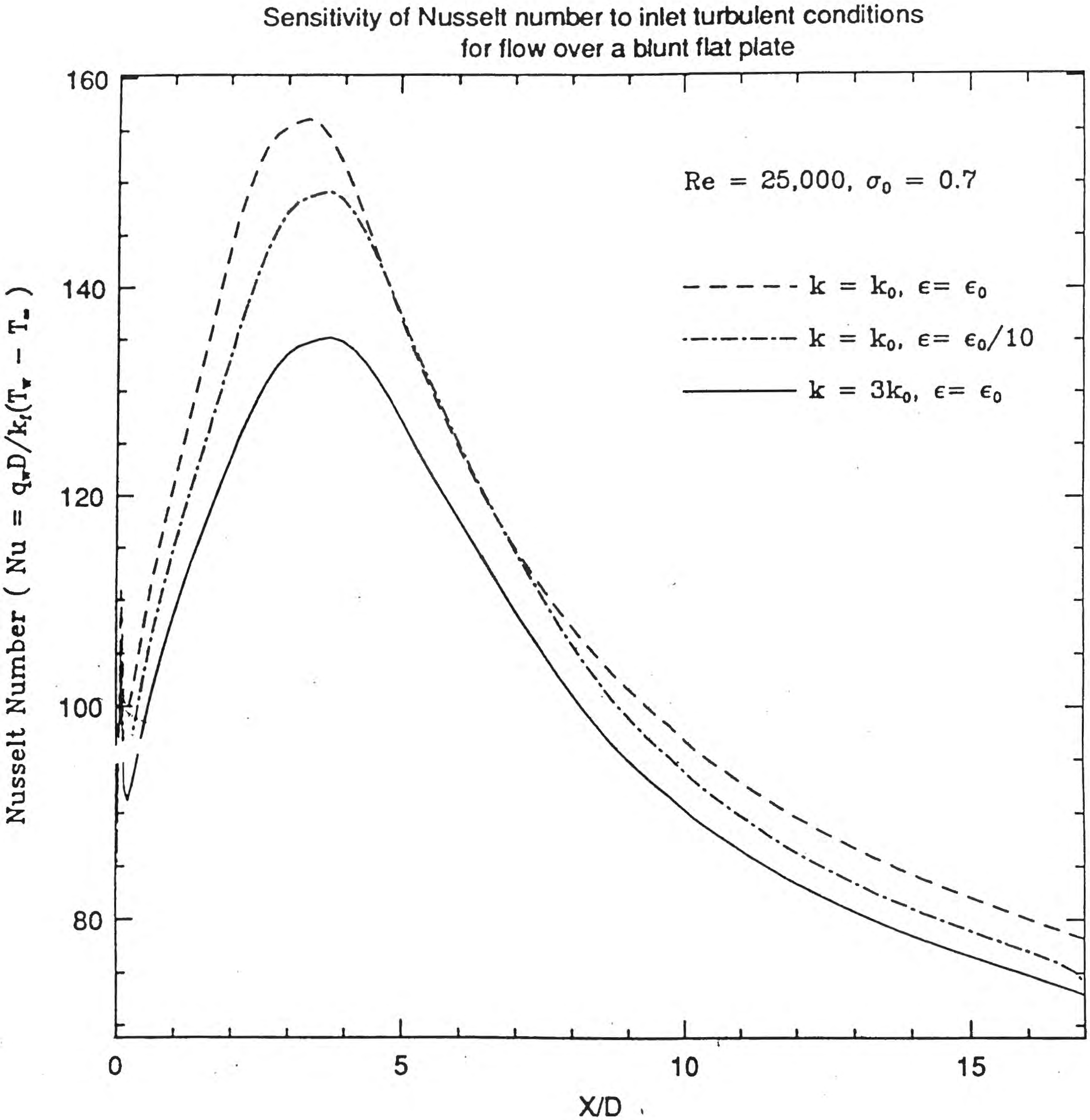
Streamlines for the flow in a turnaround duct computed using the standard K− ε model

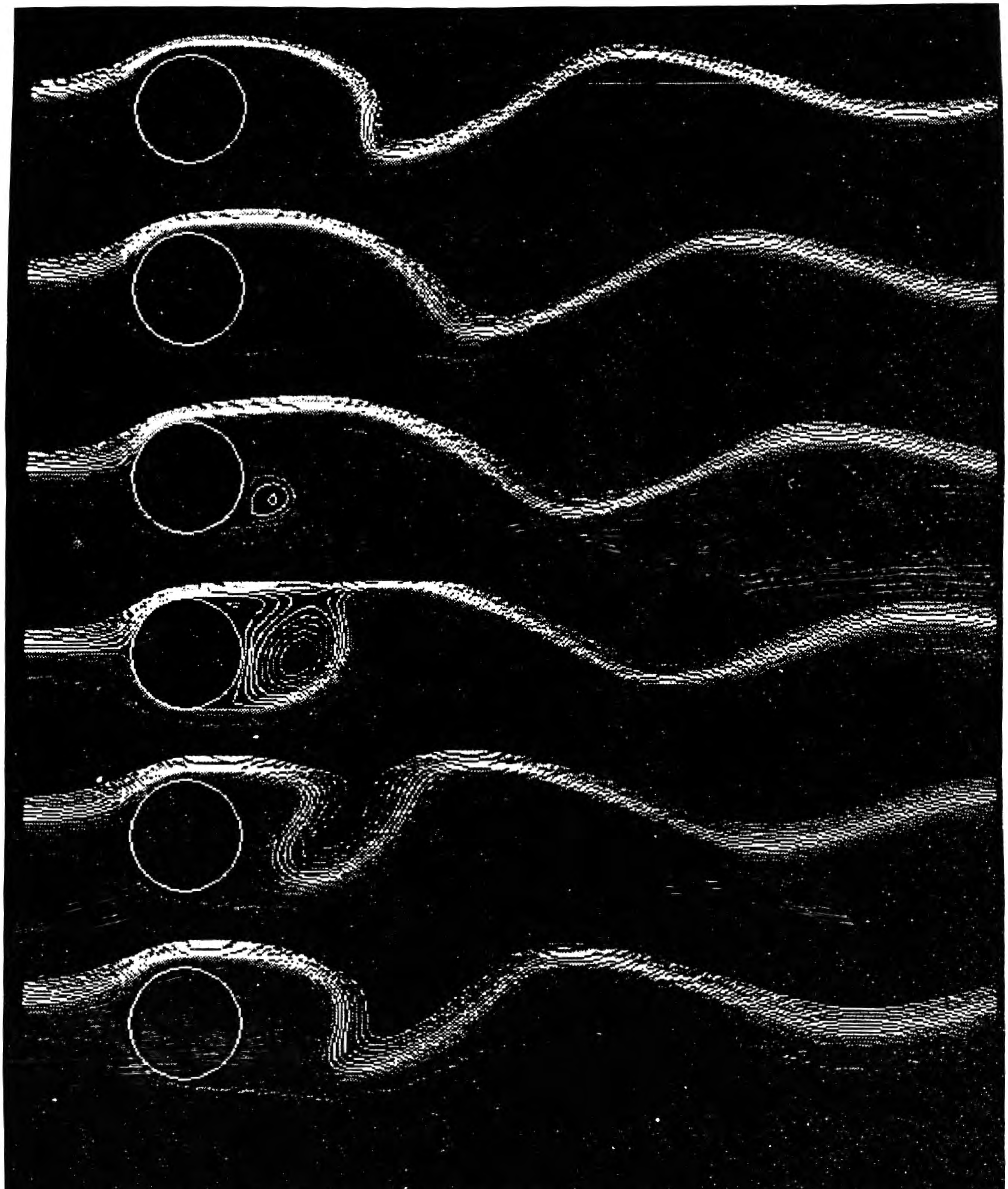


Streamlines for the flow in a turnaround duct computed using RNG K – ε Model (Re = 10^5)

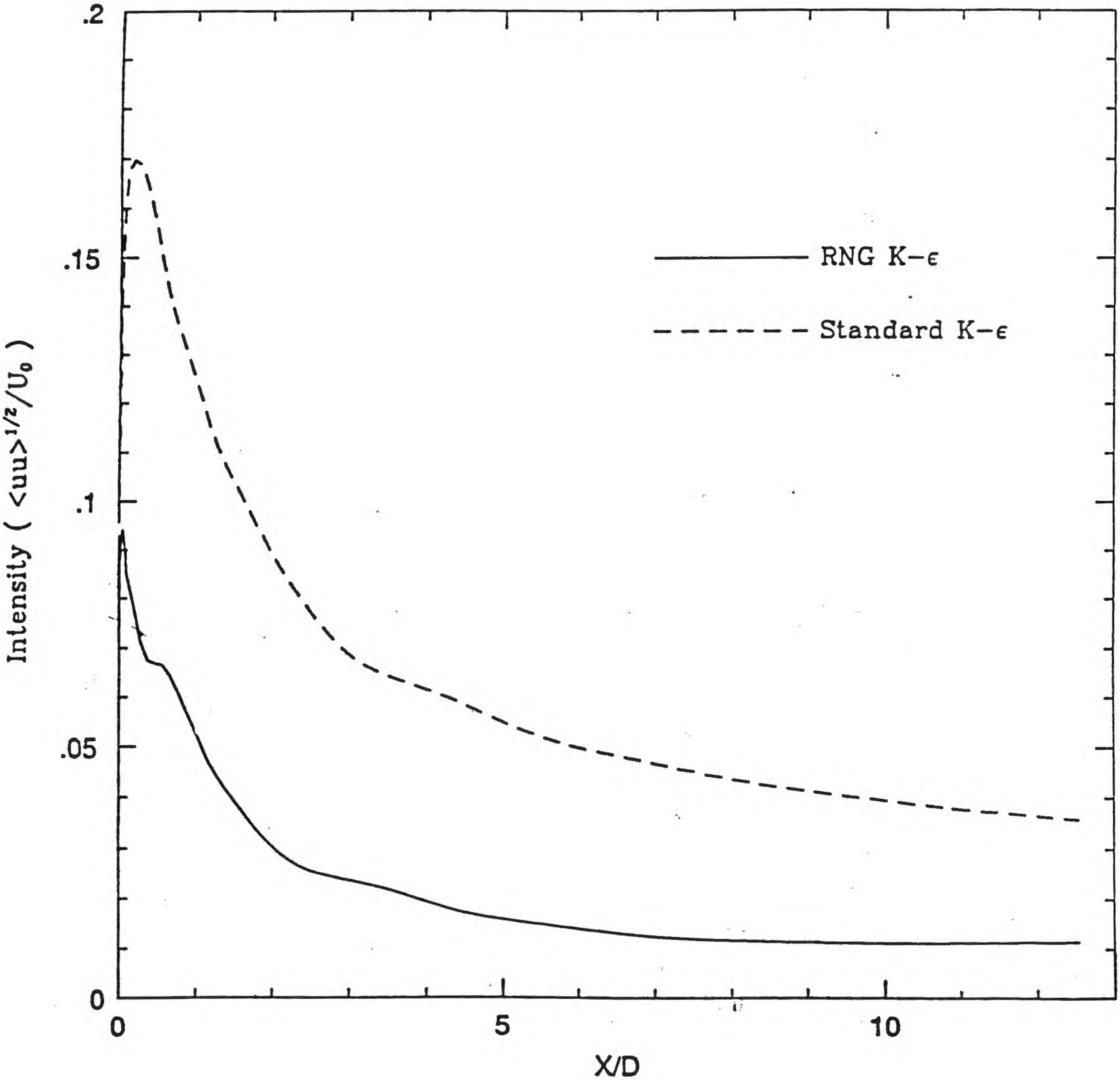


Streamlines for the flow over a blunt flat plate computed using
a) the RNG $K-\varepsilon$ model b) the standard $K-\varepsilon$ model ($Re = 21,600$)

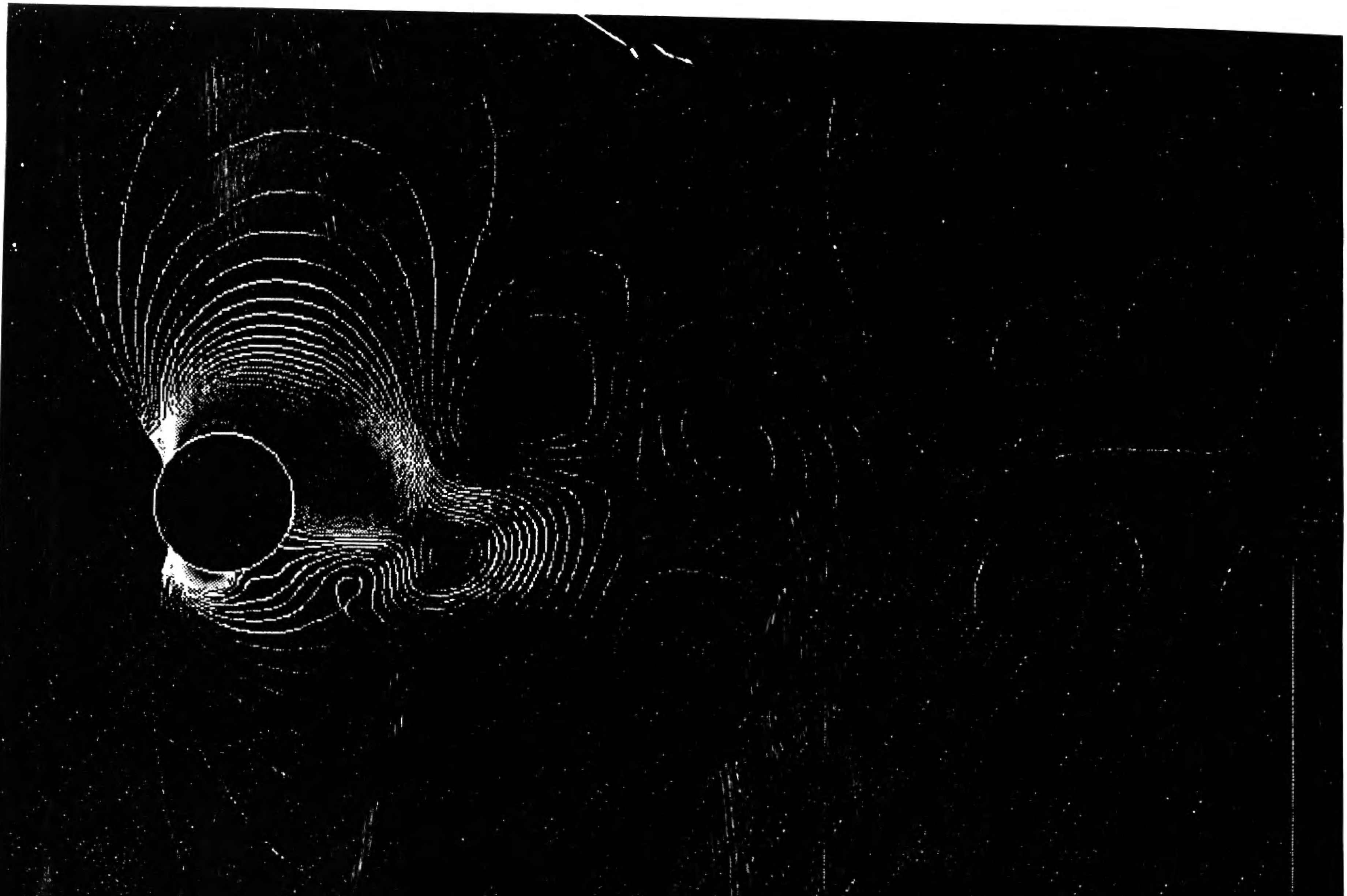

Sensitivity of Nusselt number to inlet turbulent conditions
for flow over a blunt flat plate
Re = 25,000, σ_0 = 0.7
$k = k_0$, $\epsilon = \epsilon_0$
$k = k_0$, $\epsilon = \epsilon_0/10$
$k = 3k_0$, $\epsilon = \epsilon_0$
Nusselt Number ($Nu = q_w D/k_f(T_w - T_\infty)$)
X/D
160
140
120
100
80
0
5
10
15



Streamlines in the wake of a cylinder at Re=14,500 computed using the RNG K−ε Model



Comparison between the RNG and standard K-ε models of the average turbulence intensity in the wake of the cylinder at Re = 14,500.



Pressure contours in the flow over a cylinder at Re = 14,500 computed using the RNG K- ε Model

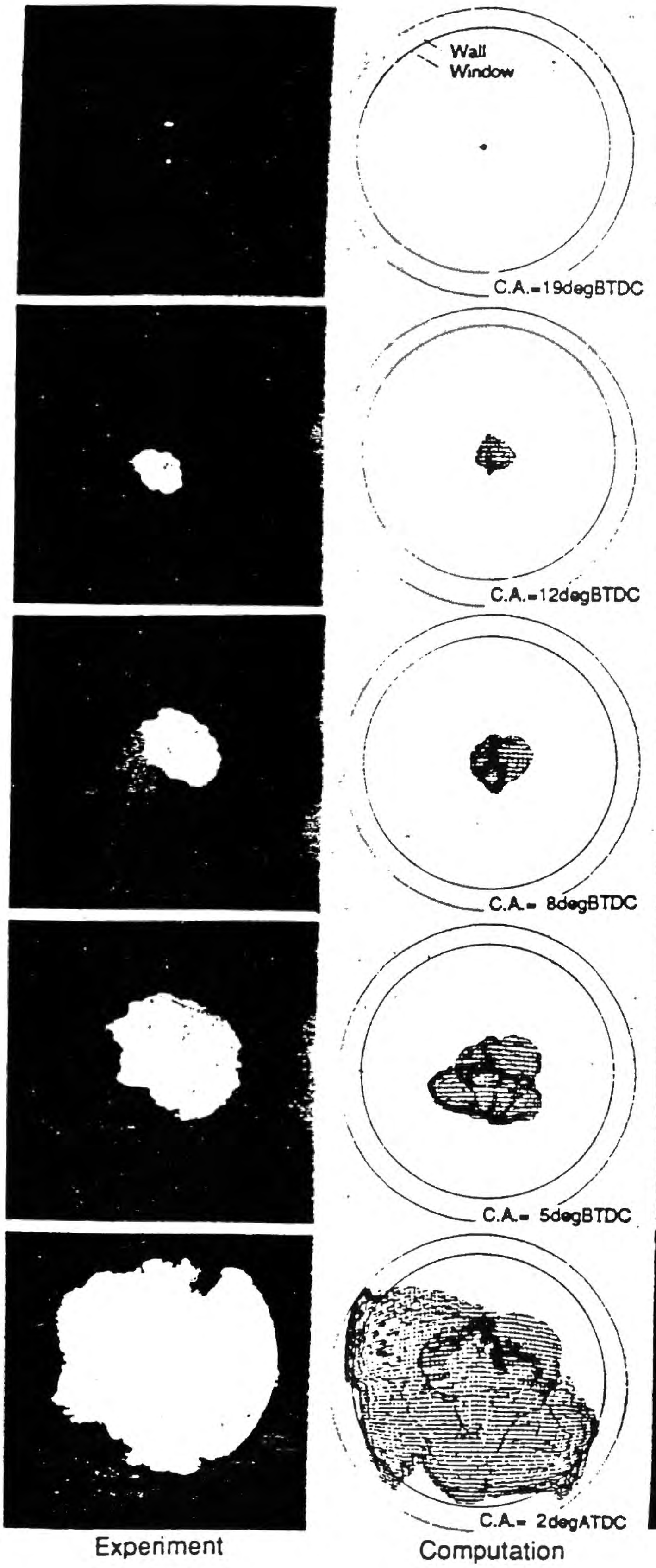


Fig. 11 The computed and experimental flame-propagation process in a 4-valve engine (CASE A-II) Engine speed =1400rpm,

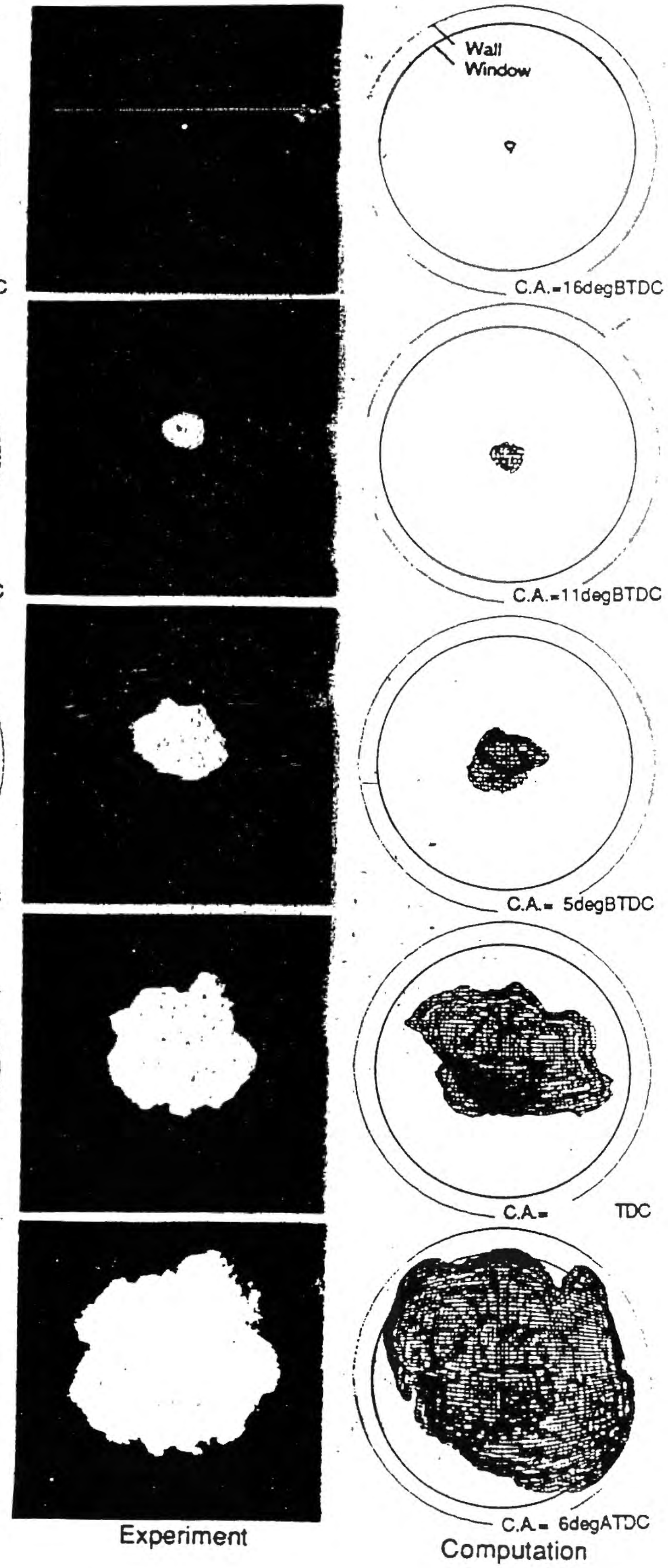


Fig. 12 The computed and experimental flame-propagation process in a 4-valve engine (CASE A-III) Engine speed =2100rpm,

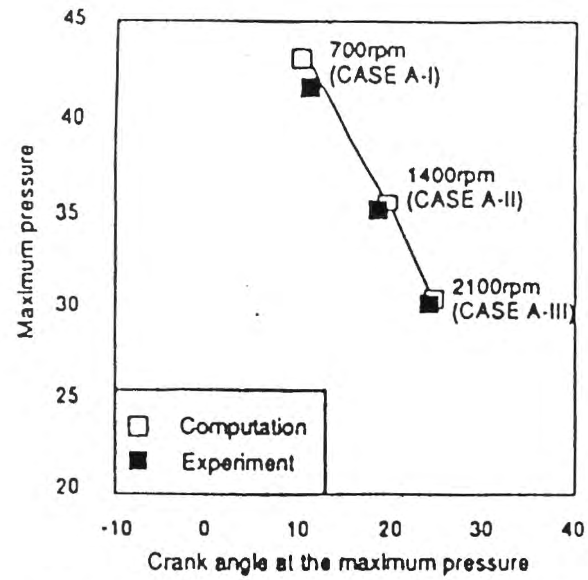


Fig.14 The comparison of the computed maximum pressure with the experimental data (Engine speed variation)

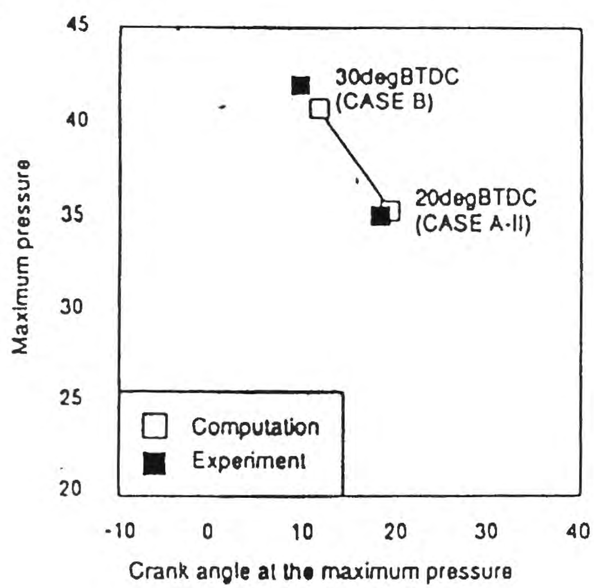


Fig.15 The comparison of the computed maximum pressure with the experimental data (Ignition timing variation)

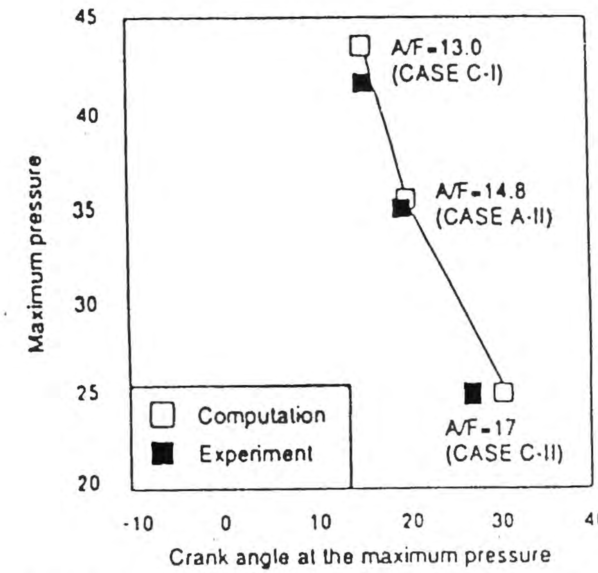


Fig.16 The comparison of the computed maximum pressure with the experimental data (A/F ratio variation)

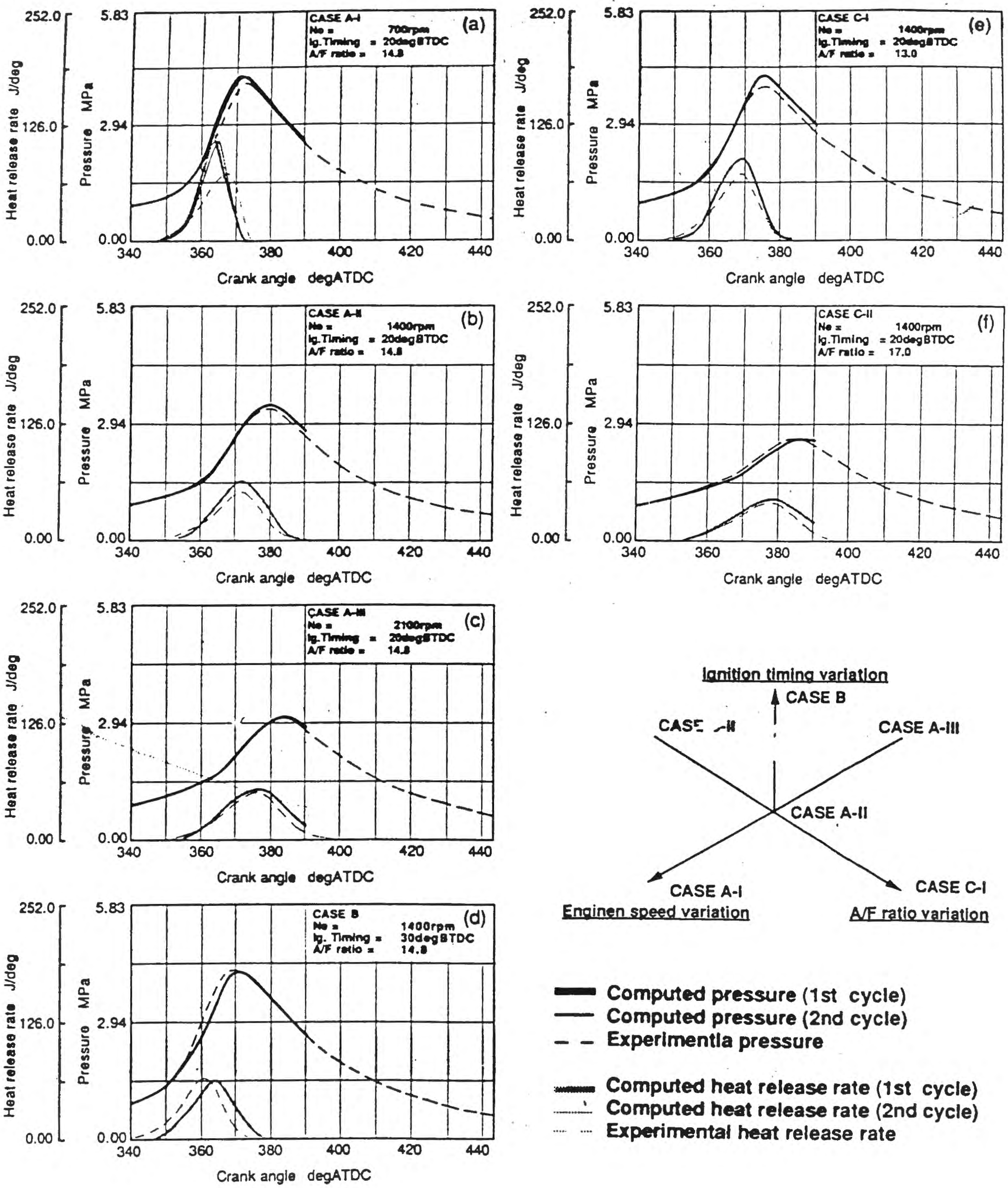


Fig. 13 The time histories of the computational- pressure and heat release rate and the corresponding experiments
(a) CASE A-I, (b) CASE A-II, (c) CASE A-III,
(d) CASE B, (e) CASE C-I, (f) CASE C-II

RNG Turbulence Modeling

1. Continuous spectrum of models
   DNS → LES → RANS
   - Determined by mode cut off

2. Basic physics models are key
   - Derivation
   - Test / Even simple models can have a lot of physics built in
     \ Understand limits of validity of model

3. K-ε OK for general separated, non-equilibrium flows

   OK up to swirl #s O(1)
   Anisotropic mod'ns needed for larger swirl #s
   Limits yet unknown but RSM may not be needed

4. Turbulence structure can be obtained by modeling even at K-ε level

5. DNS may be at misleadingly low Re
   - Models critical

Reverse Blank

3. Direct Control of Wall Shear-Stress in a Turbulent Boundary Layer

Daniel Nosenchuck and Garry Brown
Princeton University

SEMINAR NOTICE

DIRECT CONTROL OF WALL TURBULENCE USING ELECTROMAGNETIC FORCES

Professor Daniel M. Nosenchuck

and

Professor Garry L. Brown

Princeton University

A new concept and technique has been developed to directly control turbulence production in boundary layers. Near-wall vertical motions are directly suppressed through the application of a Lorentz force. Current ($\boldsymbol{j}$) and magnetic ($\boldsymbol{B}$) fields parallel to the boundary and normal to each other produce a finite Lorentz force $\boldsymbol{j} \times \boldsymbol{B}$ normal to the boundary. Experiments have been performed on flat-plate turbulent boundary layers at $Re_\theta = 1700$. With the application of modest field densities (eg. $|\boldsymbol{B}| < 500$ gauss and $|\boldsymbol{j}| < 10\ \mathrm{mA/cm^2}$), measured reductions in turbulent stresses within the control region are seen to exceed 90%. Laser-sheet flow visualization confirms the substantial reductions in turbulent motion at $y^+ \lesssim 15$. It is suggested that the principal reason for the observed effects is due to the direct control of the coherent motions responsible for turbulence production in the near-wall region.

Thursday, 24th September 1992

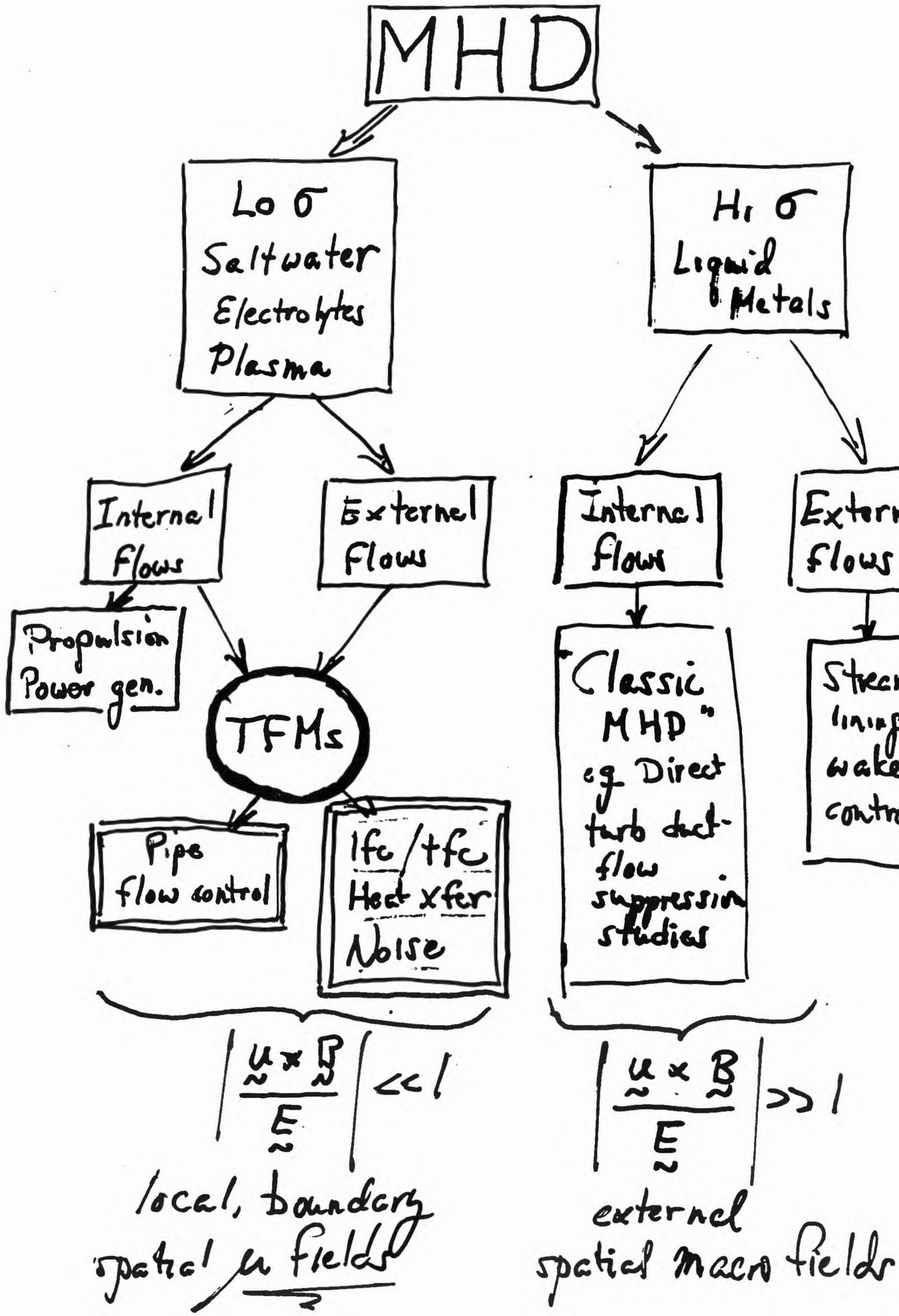
Conference Room A, Bldg. 102

Time: 10:30 AM

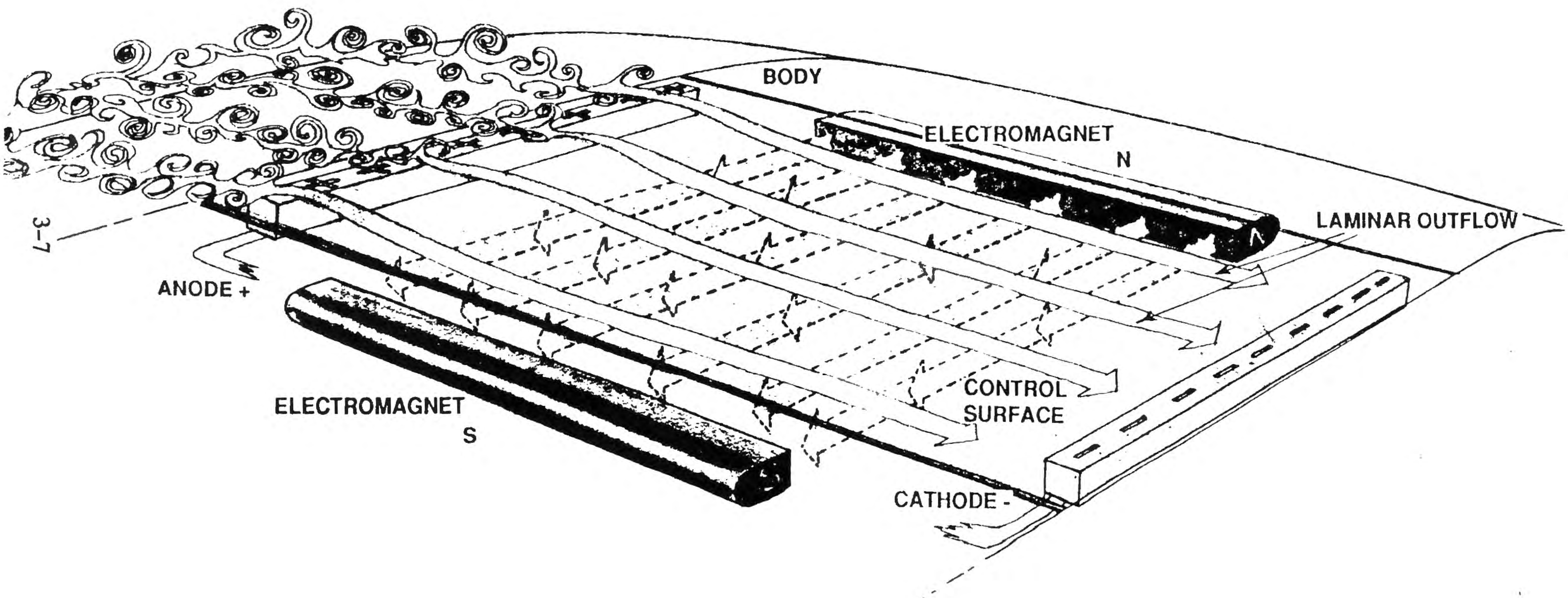
POC: Dr. Promode R. Bandyopadhyay (Code 8234; x2588)

Overview

- Turbulence is characterized by:
  - periodic eruptions of unstable, low-momentum 'near-wall' fluid
  - subsequent inrush of high-speed 'outer-flow' fluid
  - resultant large skin-friction drag
- Lorentz force easily generated:
  - surface electrodes produce electric field with current density j
  - magnetic field B is generated parallel to surface and normal to electric field
  - resultant normal force is $j \times B$
- Direct application of wall-normal force could prohibit lift-up and bursting of near-wall fluid


MHD
Lo σ
Saltwater
Electrolytes
Plasma
Hi σ
Liquid
Metals
Internal
flows
External
flows
Internal
flows
External
flows
Propulsion
Power gen.
TFMs
Pipe
flow control
lfc/tfc
Heat xfer
Noise
"Classic
MHD"
eg. Direct
turb duct-
flow
suppression
studies
Stream-
lining;
wake
control
$\left|\frac{\underset{\sim}{u} \times \underset{\sim}{B}}{\underset{\sim}{E}}\right| \ll 1$
local, boundary
spatial μ fields
$\left|\frac{\underset{\sim}{u} \times \underset{\sim}{B}}{\underset{\sim}{E}}\right| \gg 1$
external
spatial macro fields

TFM Detailed Concept



Elementary Concepts
MHD Similarity

- Assume 1-D flow; applied magnetic field B_0, characteristic length L, velocity U, conductivity σ, density ρ, viscosity μ, permeability C_μ
- Per unit volume:

$$F_v(\text{viscous force}) \sim \mu \frac{U}{L^2}$$

$$F_i(\text{inertia force}) \sim \rho \frac{U^2}{L}$$

$$F_{em}(\text{electromagnetic force}) \sim \sigma B_0^2 U$$

- Magnetic Reynolds Number (Re_m)

$$Re_m = \left(\frac{\text{induced magnetic field}}{\text{applied magnetic field}}\right) = \frac{C_\mu \sigma B_0 U L}{B_0} = C_\mu \sigma U L$$

- Hartmann number (Ha)

$$Ha = \sqrt{\frac{F_{em}}{F_v}} \equiv B_0 L \sqrt{\frac{\sigma}{\mu}}$$

- Interaction Parameter (I) (or Stuart Number)

$$I = \frac{F_{em}}{F_i} \equiv \frac{\sigma B_0^2 L}{\rho U}$$

Theoretical Considerations

- MOMENTUM

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \mathbf{L} + \mu \nabla^2 \mathbf{u}$$

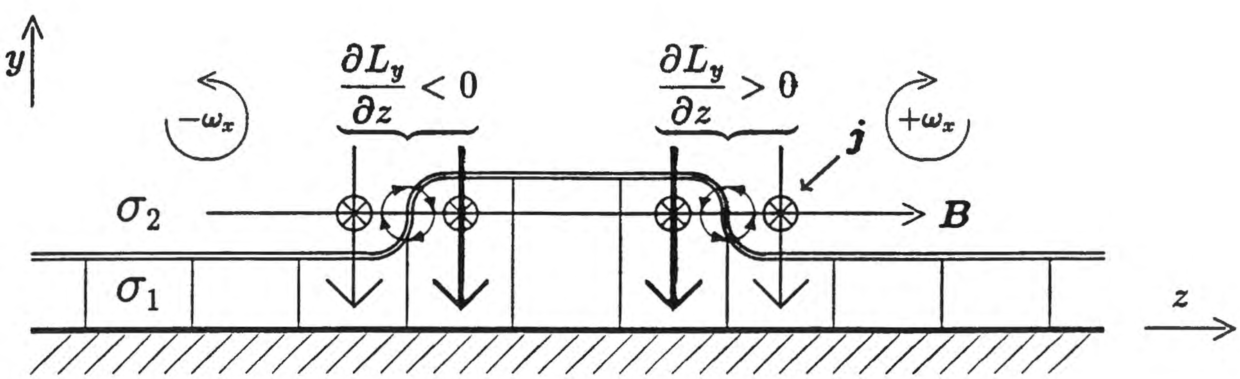
where $\mathbf{L} = \mathbf{j} \times \mathbf{B}$ (Lorentz force)

- VORTICITY

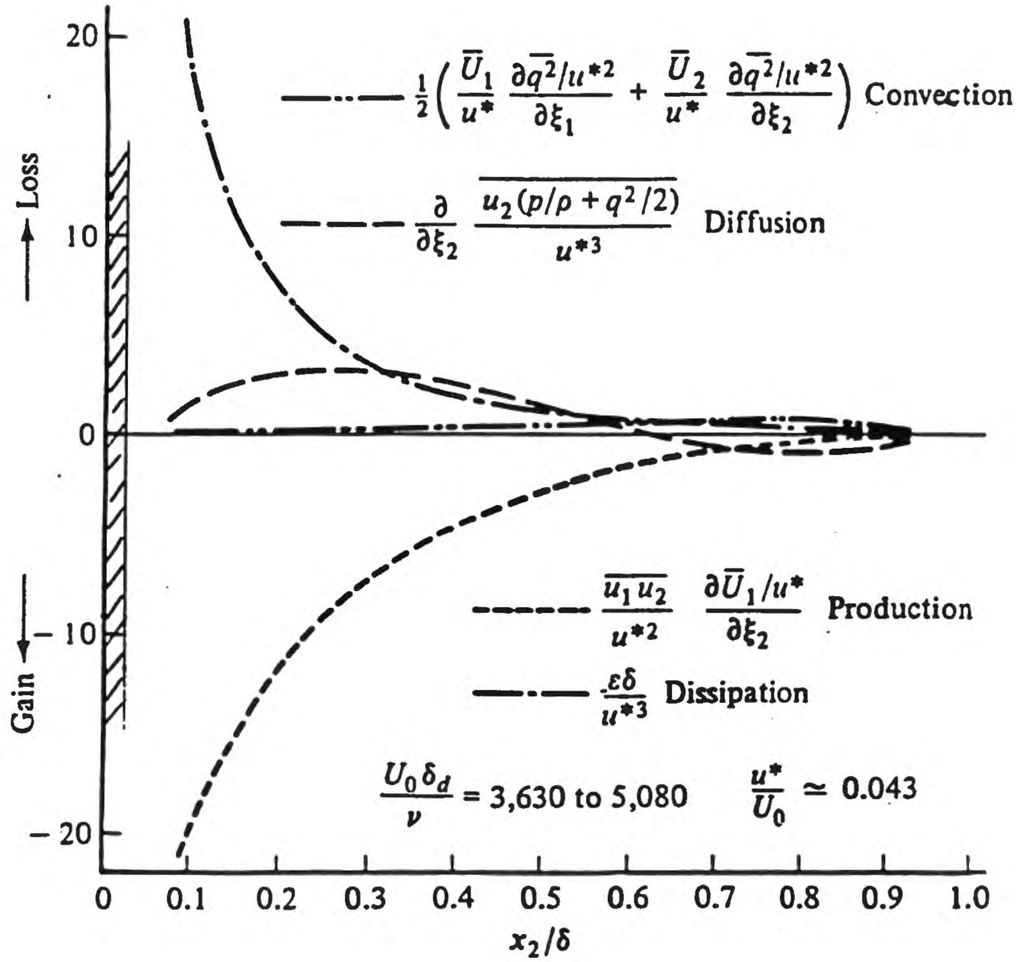
$$\rho \frac{D\omega}{Dt} = \rho\omega \cdot \nabla\mathbf{u} + \nabla \times \mathbf{L} + \mu \nabla^2 \omega$$

If $\mathbf{L} = L_y e_j$:

$$\rho \frac{D\omega_x}{Dt} = \rho\omega \cdot \nabla\mathbf{u} - \frac{\partial L_y}{\partial z} + \mu \nabla^2 \omega_x$$



Turbulent Boundary Layer Energy Balance



////////////////////// : **MTC Control Layer**

Theoretical Considerations - Continued

- ENERGY

Near the wall

$$-u'v'\frac{\partial \overline{u}}{\partial y} \simeq \frac{\overline{L'_y v'}}{\rho} + \epsilon$$

Production $\simeq$ Lorentz Work $+$ Dissipation

this suggests the nondimensional parameter

$$\frac{\Delta L\ \nu}{\rho\ u_\tau^3}$$

for scaling Magnetic Turbulence Control

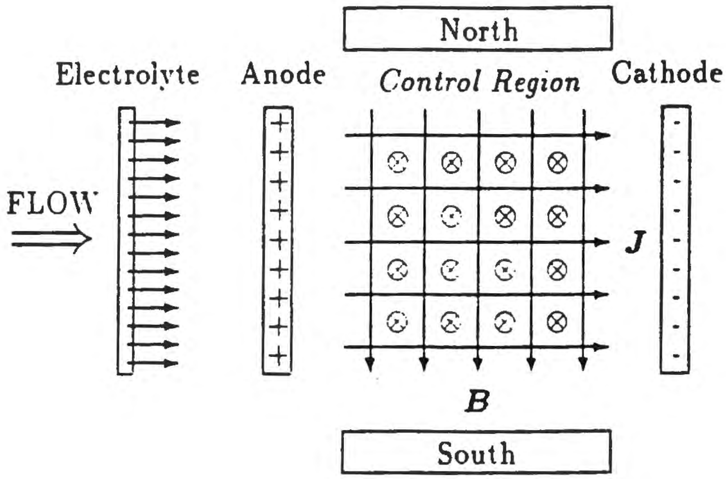
Some Engineering Considerations

- Fluid must be electrically conducting:
  - sea-water is an ideal electrolyte
  - small amounts of electrolytes injected near wall in fresh-water experiments
  - gaseous flows may be seeded with ions if plasma is not naturally present
- MTC power infinitesimal since
  - little mechanical work is done: $\overline{j \times B \cdot u} \sim 0$
  - Joule heating (σe^2) can be made negligibly small
- j and B fields may be DC or AC
- Distributed electrodes and magnet poles could generate fields that conform to non-planar surfaces

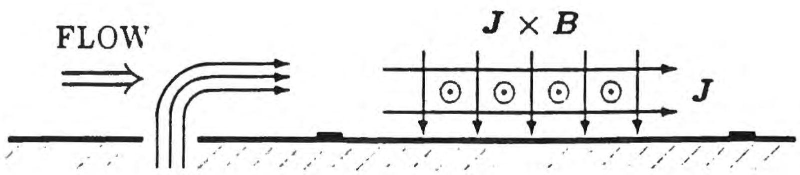
Experimental Investigation of MTC

- Turbulent boundary layer and turbulent-spot flows were studied on a flat plate in water
- Control region 8 cm wide and 16 cm long ($\sim$ 500 $\times$ 1,000 wall units) on ℄ of plate 200 cm from L.E.
- Control zone consisted of a lucite plate with
  - permanent magnets $\Rightarrow$ transverse field ($B_y \sim 500$ gauss)
  - stainless-steel surface-mounted electrodes $\Rightarrow$ longitudinal field ($0.003 < j_x < 20$ mA/cm^2)
- $800 < Re_\theta < 1700$ upstream of control zone
- Dilute HCl, NaCl, and NaOH/fluorescein electrolyte injected normal to wall upstream of control zone
- Diagnostics included hot-film probes, gauss-meters, electric field sensors, laser-sheet flow visualization

MTC Zone on a Flat Plate

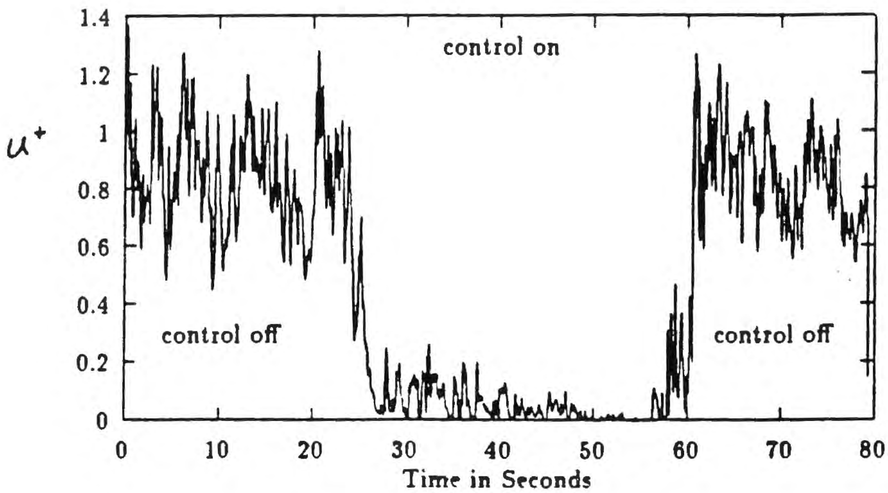


a: Planform View
($\otimes \equiv J \times B$)

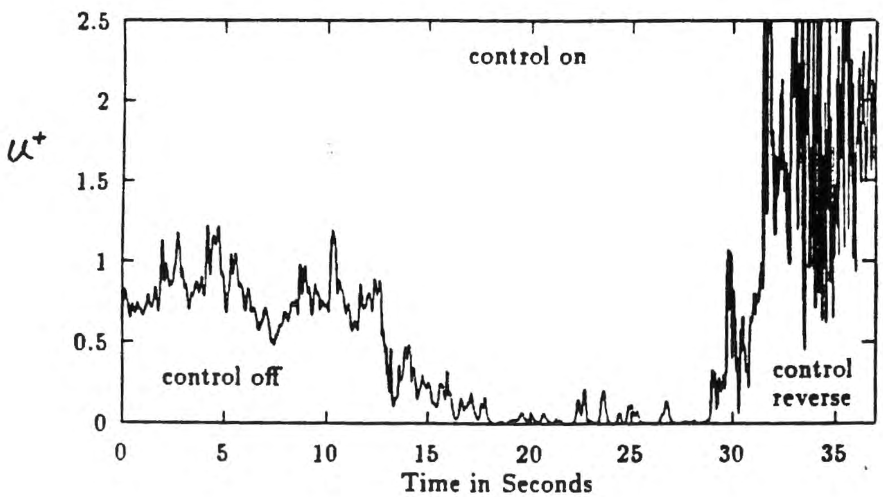


b: Elevation View
($\odot \equiv B$)

Key Results



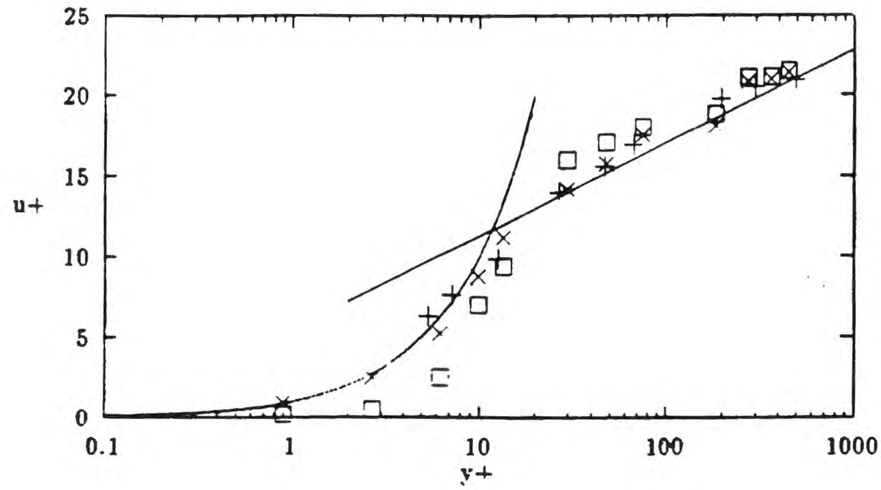
a: Control Sequence: Off-On-Off



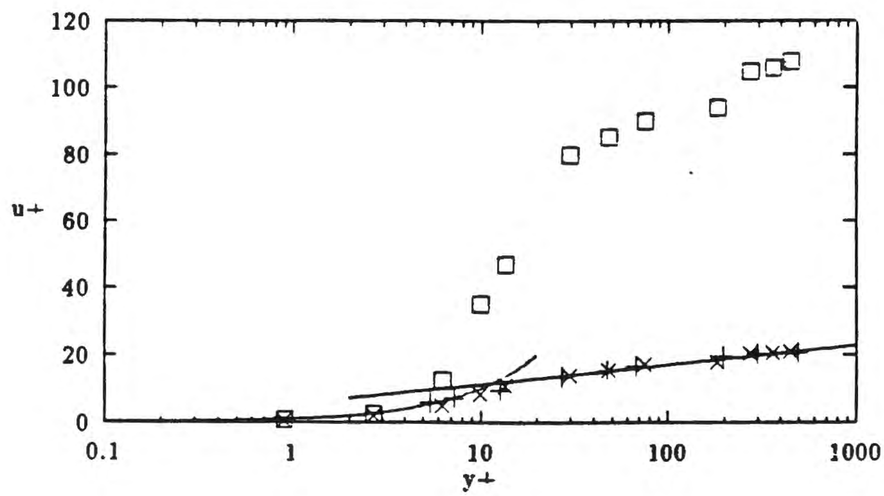
b: Control Sequence: Off-On-Reverse

MTC on Centerline at $y^+ \sim 1$
Velocity vs Time

×: No Electrolyte
+: Electrolyte On; No Control
□: Control On: $j \times B < 0$

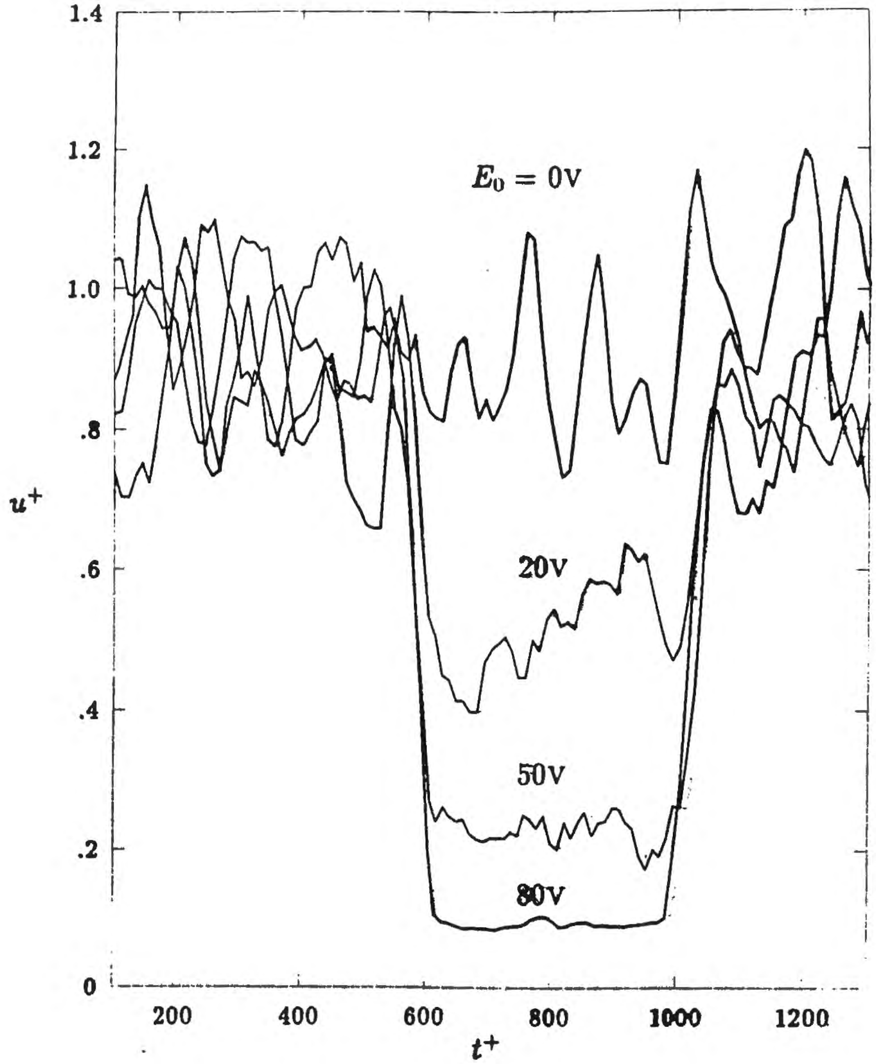


a: u_τ Computed from Baseline Profile



b: u_τ Computed for Each Case Separately

Effect of MTC on Mean Turbulent Boundary Layer Velocity Profile

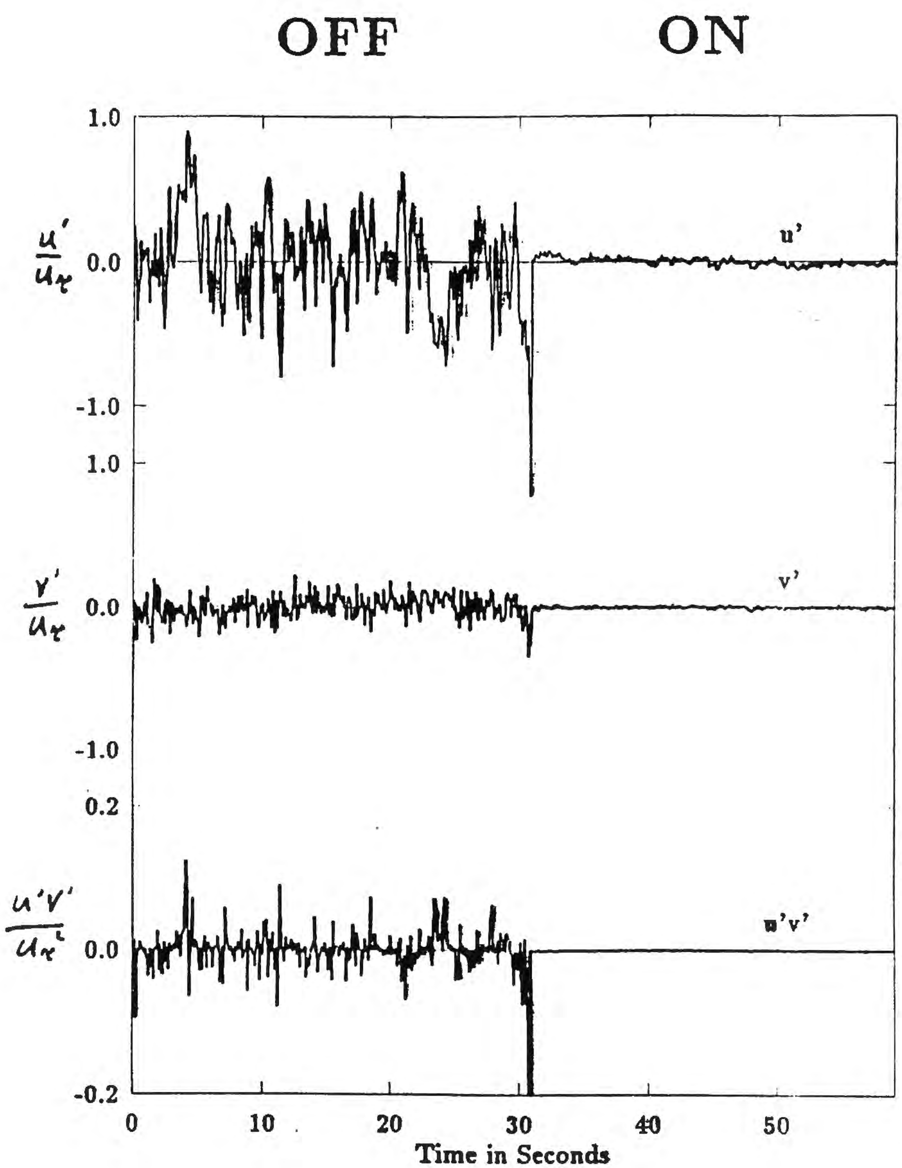


Effect of Magnitude of Lorentz Force on Magnetic Turbulence Control

Velocity vs Time

$y^+ \simeq$ [illegible] $\quad Re_\theta \simeq 1700$

Magnetic Turbulence Control

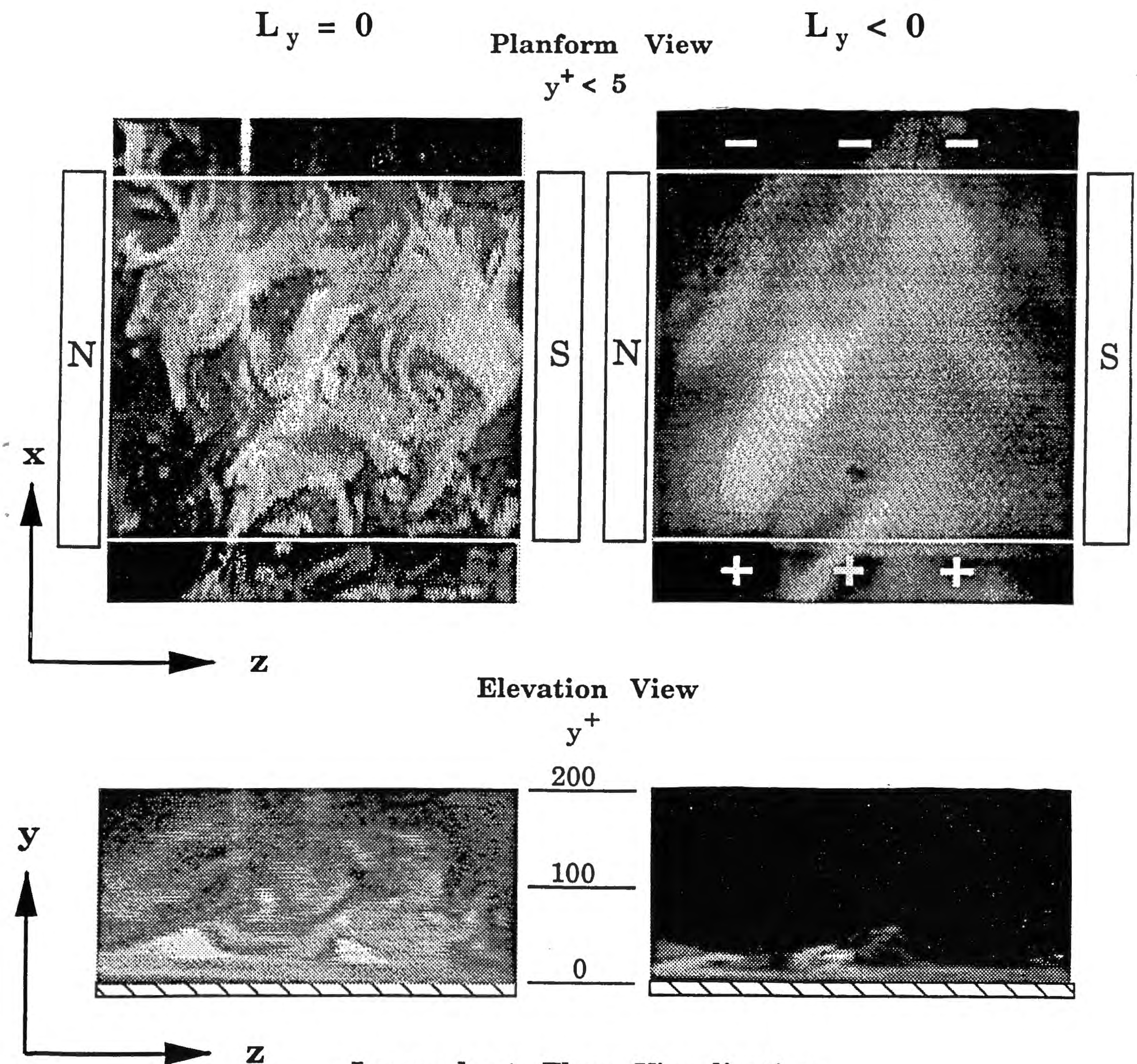


Turbulent Motions and Stresses

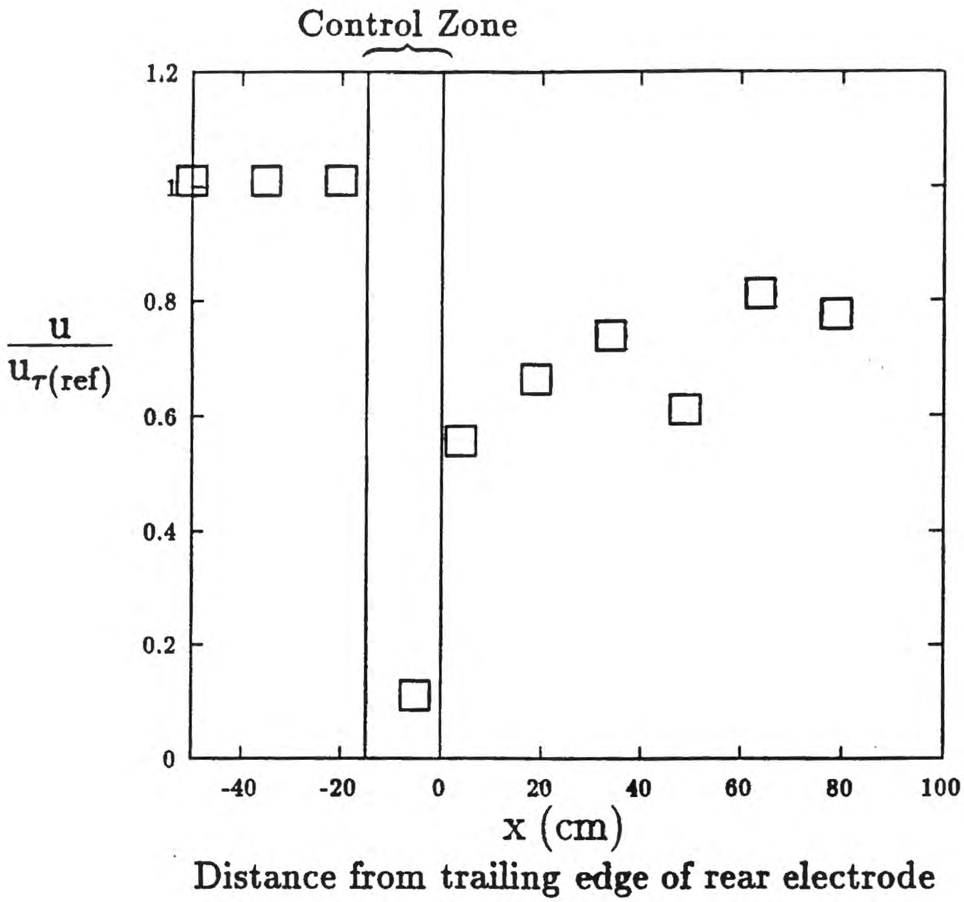
Velocity vs Time

$y^+ \sim 3 \quad Re_\theta \simeq 1100$

Direct Magnetic Control
of a Turbulent Boundary Layer



Laser-sheet Flow Visualization



MTC Relaxation

Near-wall Longitudinal Velocity (Wall-Shear) Distribution On Control Zone Centerline

(Preliminary Results)

Other Applications

- Separation control
  - decrease or increase form drag
  - provide directional control through net lateral forces and moments
- Acoustic field attenuation/enhancement/tailoring
- Modification of unsteady surface pressure fields
- Turbulent fluid mixing
- Surface heat-transfer control:
  - $j \times B < 0 \;\Rightarrow$ decreased wall heating
  - $j \times B > 0 \;\Rightarrow$ enhanced wall heating

Summary of MTC

- A new concept and technique using electro-magnetic fields has been developed to suppress wall-turbulence

- Non-intrusive magnets and surface electrodes:
  - impart normal force $j \times B$ near wall in turbulent boundary layers
  - turbulence generation directly suppressed

- Proof-of-concept experiments have been performed in a water channel on a flat plate model
  - $>$ 90% reduction in turbulent skin friction (drag)
  - near wall velocity fluctuations attenuated $> 5\times$
  - flow visualization indicates nearly 'laminar' flow
  - minimal power/current required

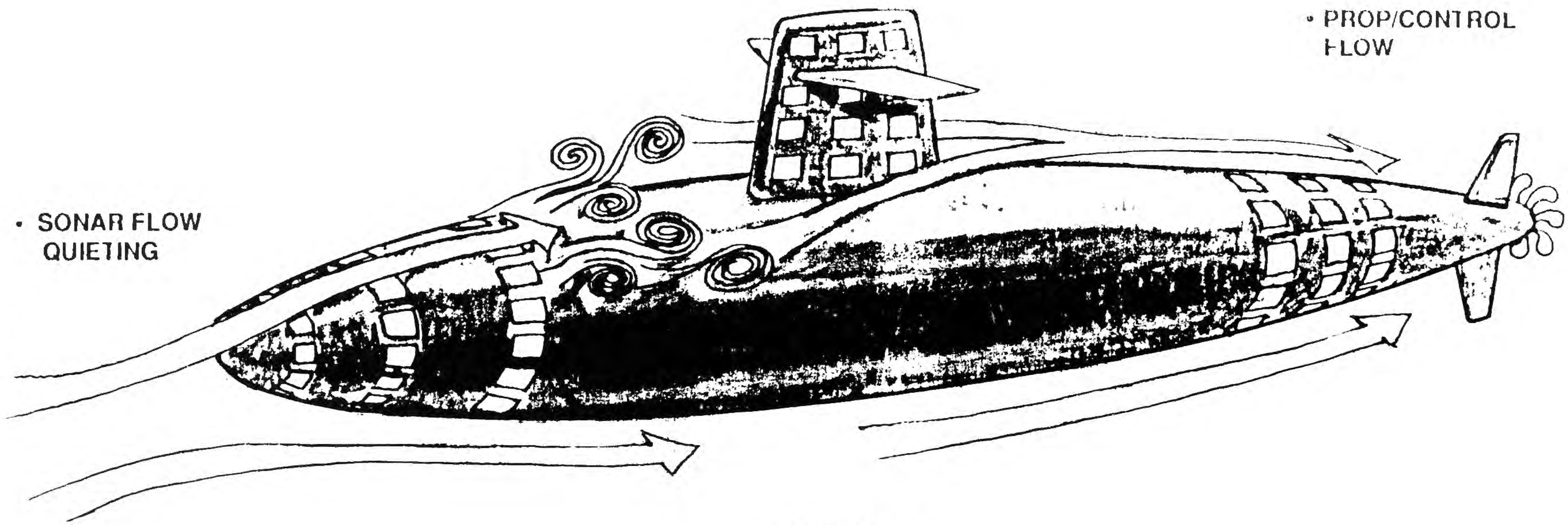
Questions

- High Reynolds number behavior
- Dependence on ion concentration and uniformity
- Underlying dimensionless parameters

$$\text{e.g.}\ \frac{\Delta L \nu}{\rho u_\tau^3}$$

- Relaxation, tiling, and three-dimensionality
- Frequency response; field attenuation
- Numerical simulation

TFM APPLICATION CONCEPT - SEA



4. Bluff-Body and Other Shear Flows

Anatol Roshko
California Institute of Technology

NUWC Division Newport, R. I.

SEMINAR NOTICE

BLUFF-BODY AND OTHER SHEAR FLOWS

Anatol Roshko

Theodore von Kármán Professor of Aeronautics

California Institute of Technology

The old problems of the far wake, near wake and forces on bluff bodies will be discussed, mainly the so-called two-dimensional flows behind circular cylinders and flat plates. Progress and problems in understanding the dynamics of the flow will be discussed. Topics include: effects of Reynolds number; effects of three dimensionality in nominally 'two dimensional flows'; roles of vortex dynamics and Reynolds stress; insights from experimental-computational interactions and from other shear flows.

Monday, 28th September 1992

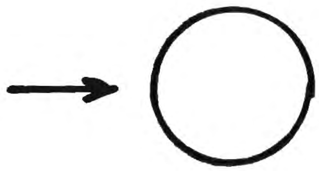
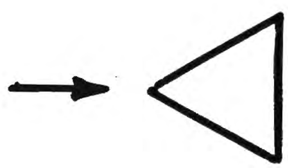
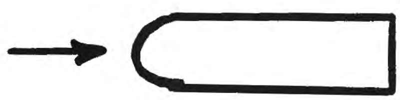
Conference Room B, Bldg. 102

Time: 10:30 AM

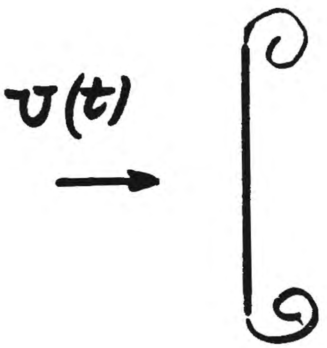
POC: Dr. Promode R. Bandyopadhyay (Code 8234; x2588)

Bluff-Body Near Wakes

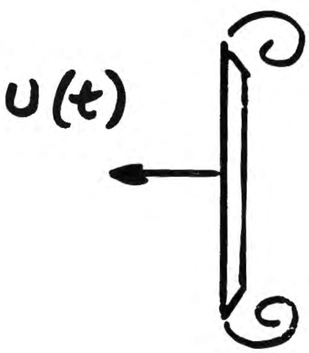
"Simple" Geometries

2D		Axisymmetric
Circular Cylinder		Sphere
Flat Plate		Disc
Wedge		Cone
Slab		Rod
Vortex Shedding		Shedding
Quasi 2D		Not axisymmetric

FLAT PLATE

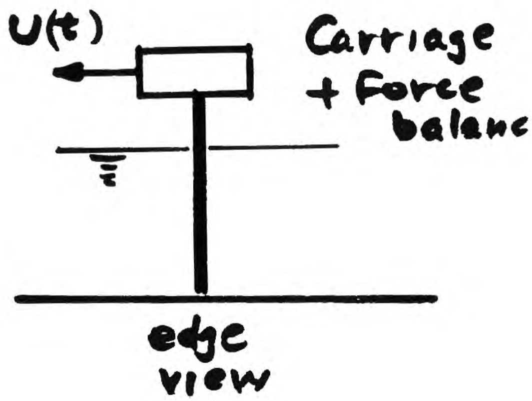


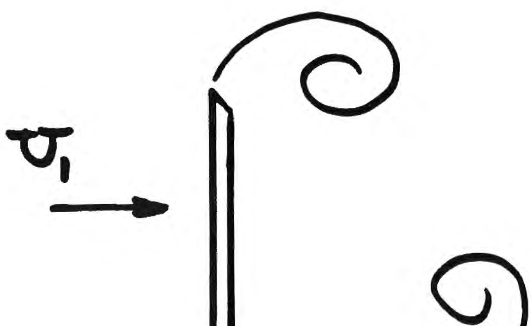
Numerical Simulation
exactly 2D



Tow Tank

nominally
2D





Free-Surface
Water Tunnel

nominally
2D, "steady"

(Also DISC?)

3 Kinds of "2D" Flows

1. Exactly 2D

Realizeable only in Numerical Simulation!
(cf soap-film "wind tunnel")

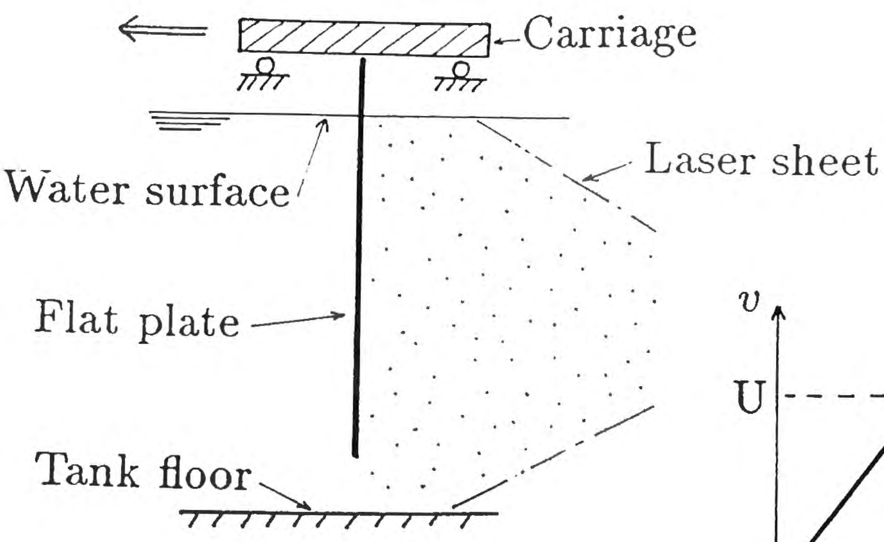
2. Real, Laboratory Flows

- End effects
- Intrinisic 3D (turbulent) motions from instability ($Re \gtrsim 10^2$)

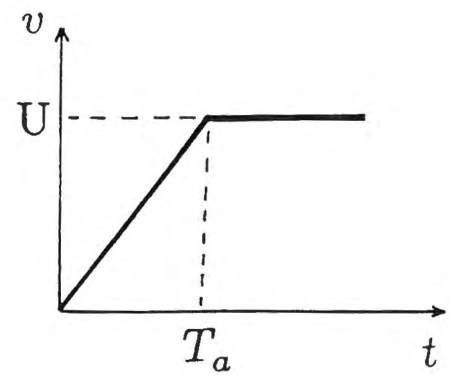
3. Idealized Real Flows

- Nominally $\overline{2D}$. Spanwise homogeneous?
- with intrinsic 3D motions
- No end effects
- These are the scientific objective.
- Degree of realizeability ?

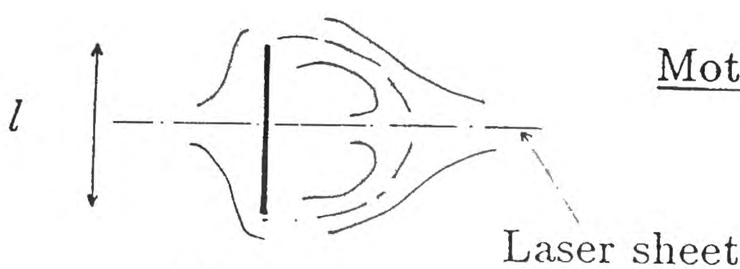
FLOW ABOUT A 2-D FLAT PLATE



Side view



Motion time history



Top view

$$U = aT_a$$

$$T_a^* = T_a\sqrt{\frac{a}{l}}$$

$$Re_U = \frac{Ul}{\nu}$$

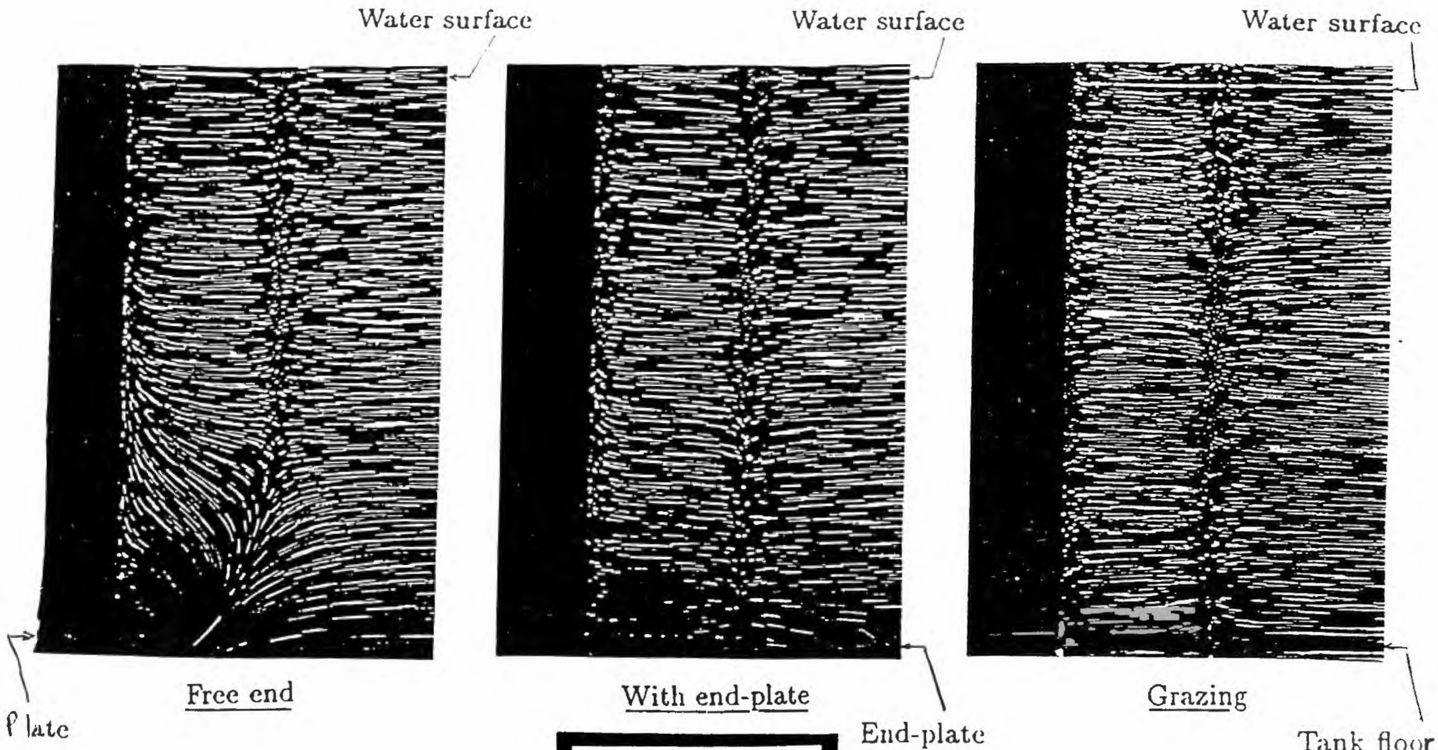
$$Re_a = \frac{l\sqrt{al}}{\nu}$$

$$t_U^* = t\frac{U}{l}$$

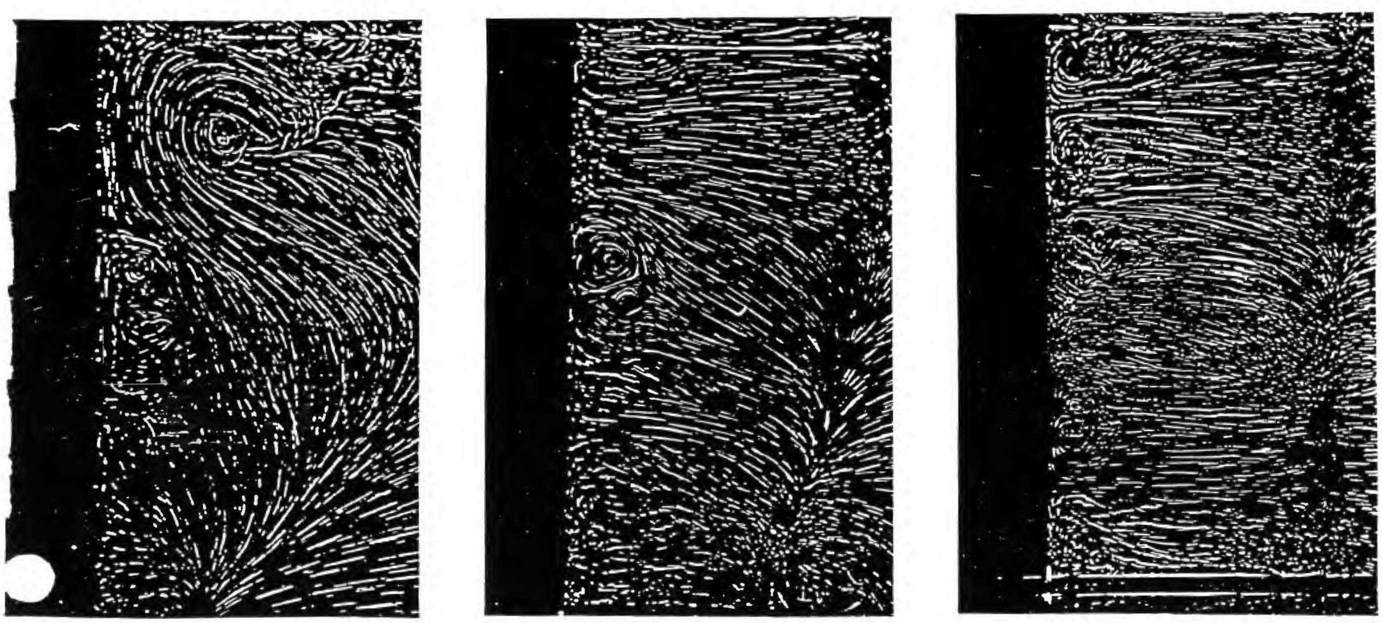
$Re_a = 3966$
$Re_U = 6096$
$T_a^* = 1.54$

Voca

END EFFECTS ON THE FLOW PAST FLAT PLATES



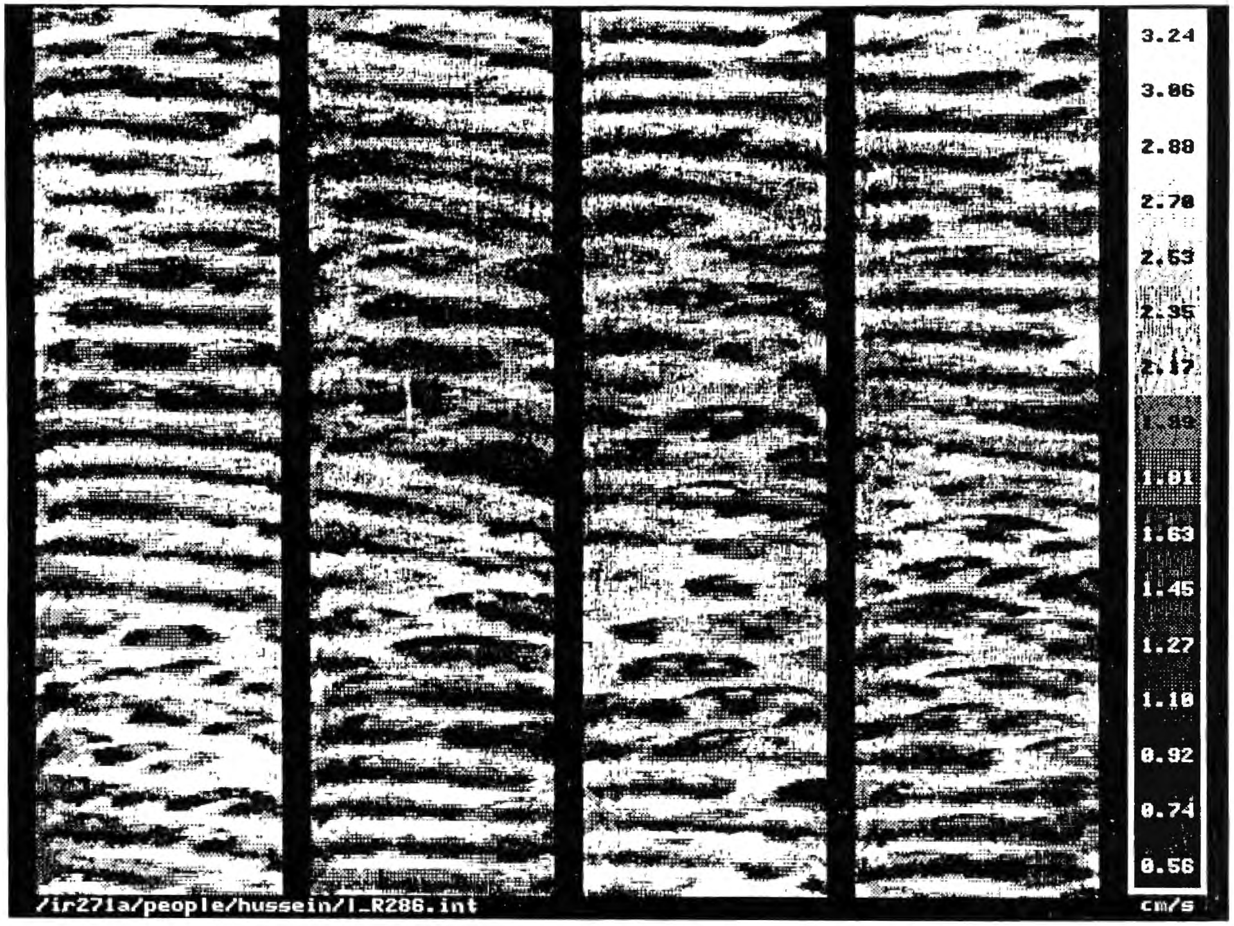
$t^* = 2.13$

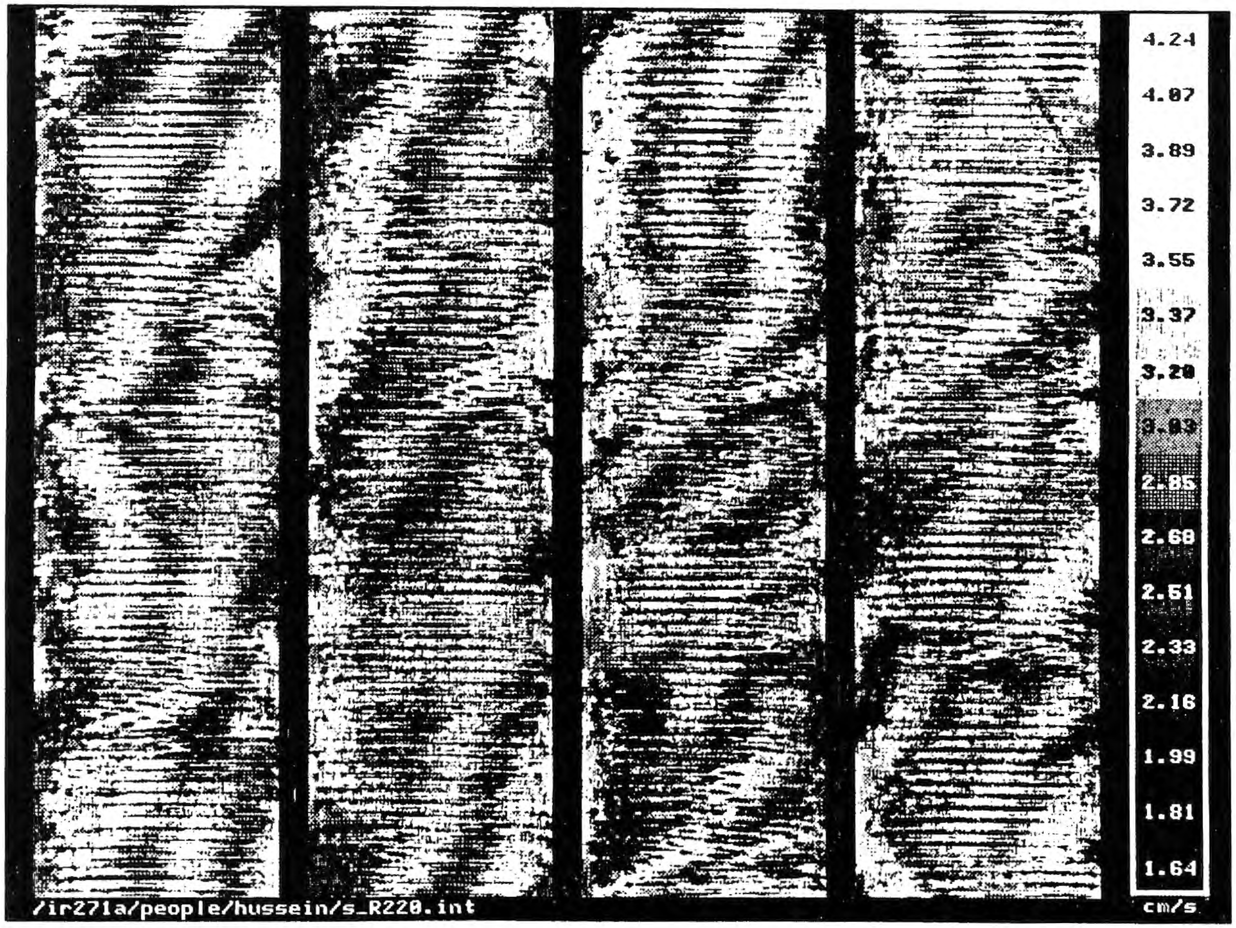


$t^* = 7.44$

NOCA

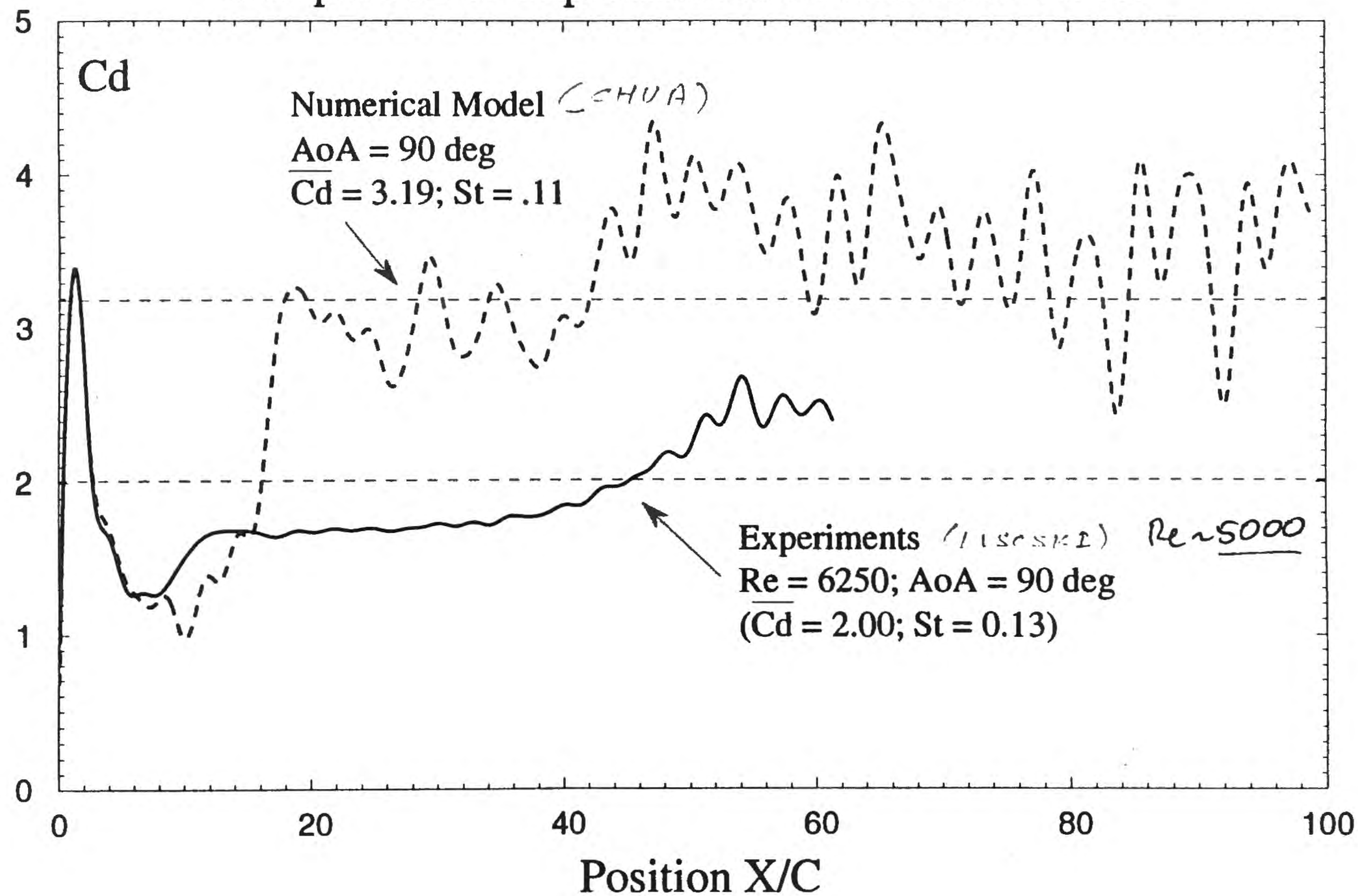
D. Williams, I.I.T





D. Williams I.I.T.

Comparison of Experiment and Numerical Model

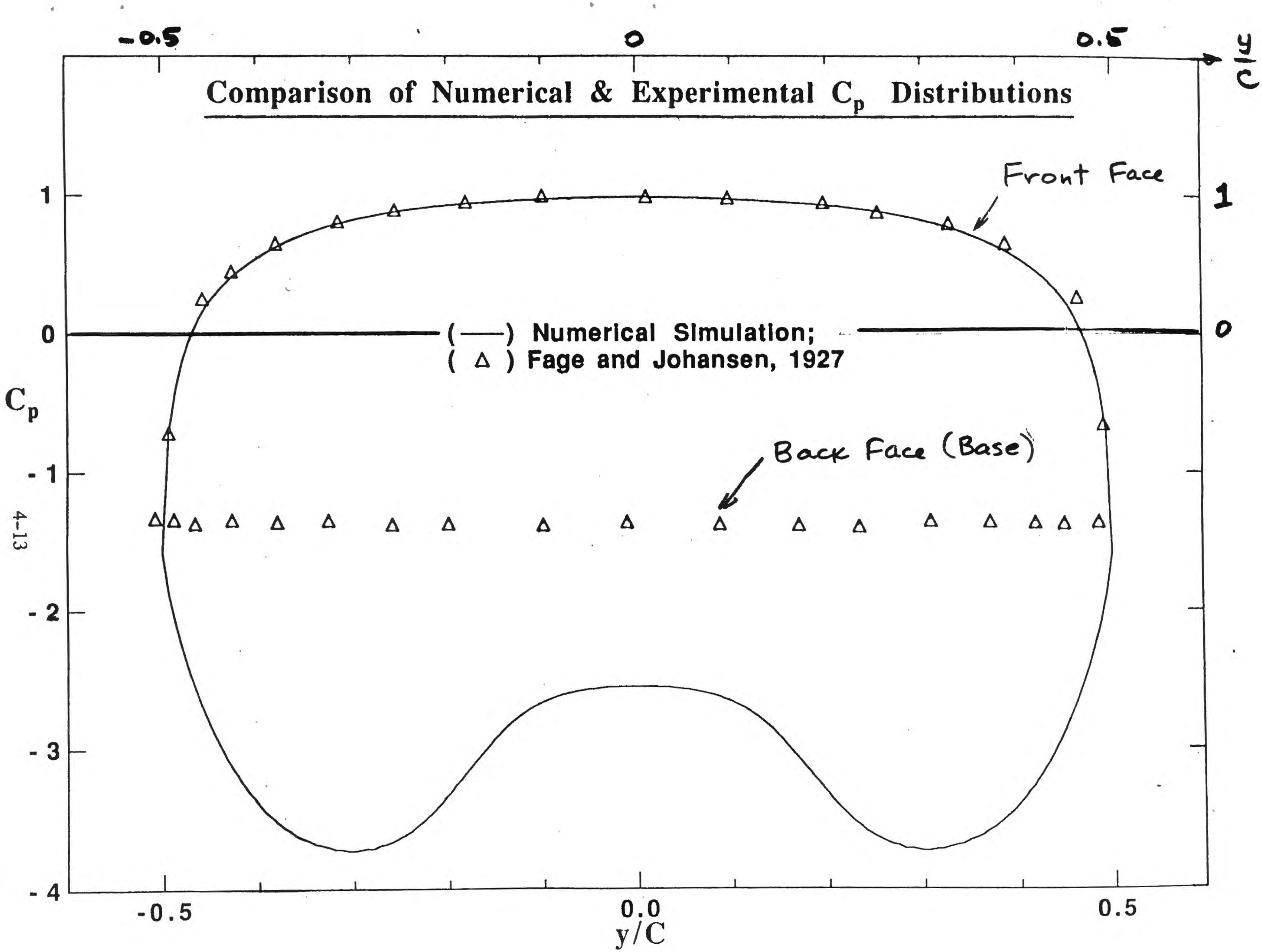


$\bar{C}_D$ from Num up to $\frac{X}{C} \approx 400$

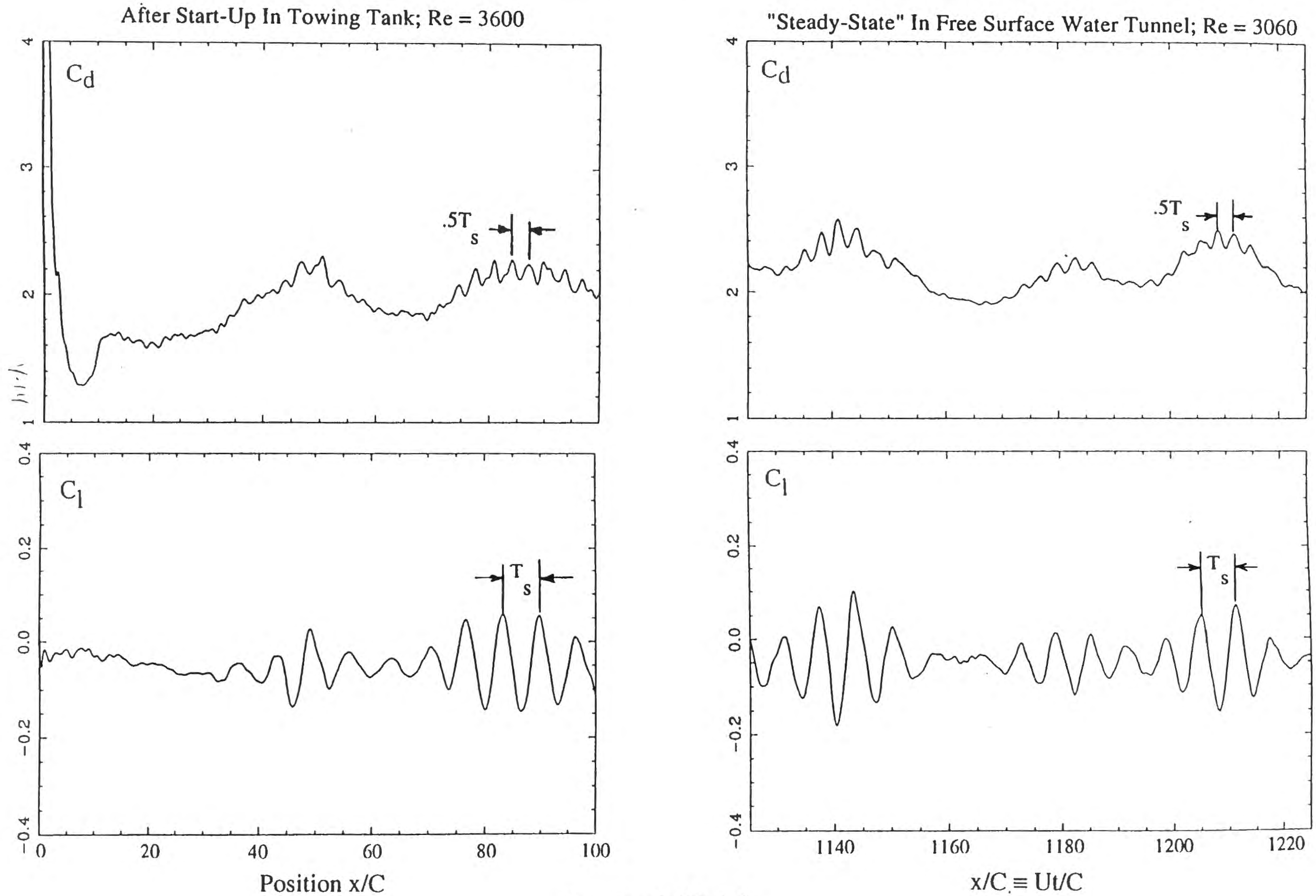
$\bar{C}_d$ from FSWT

$C = 5$ cm
$t/c = 7\%$

XY-glazing
FSWT - " false bottom

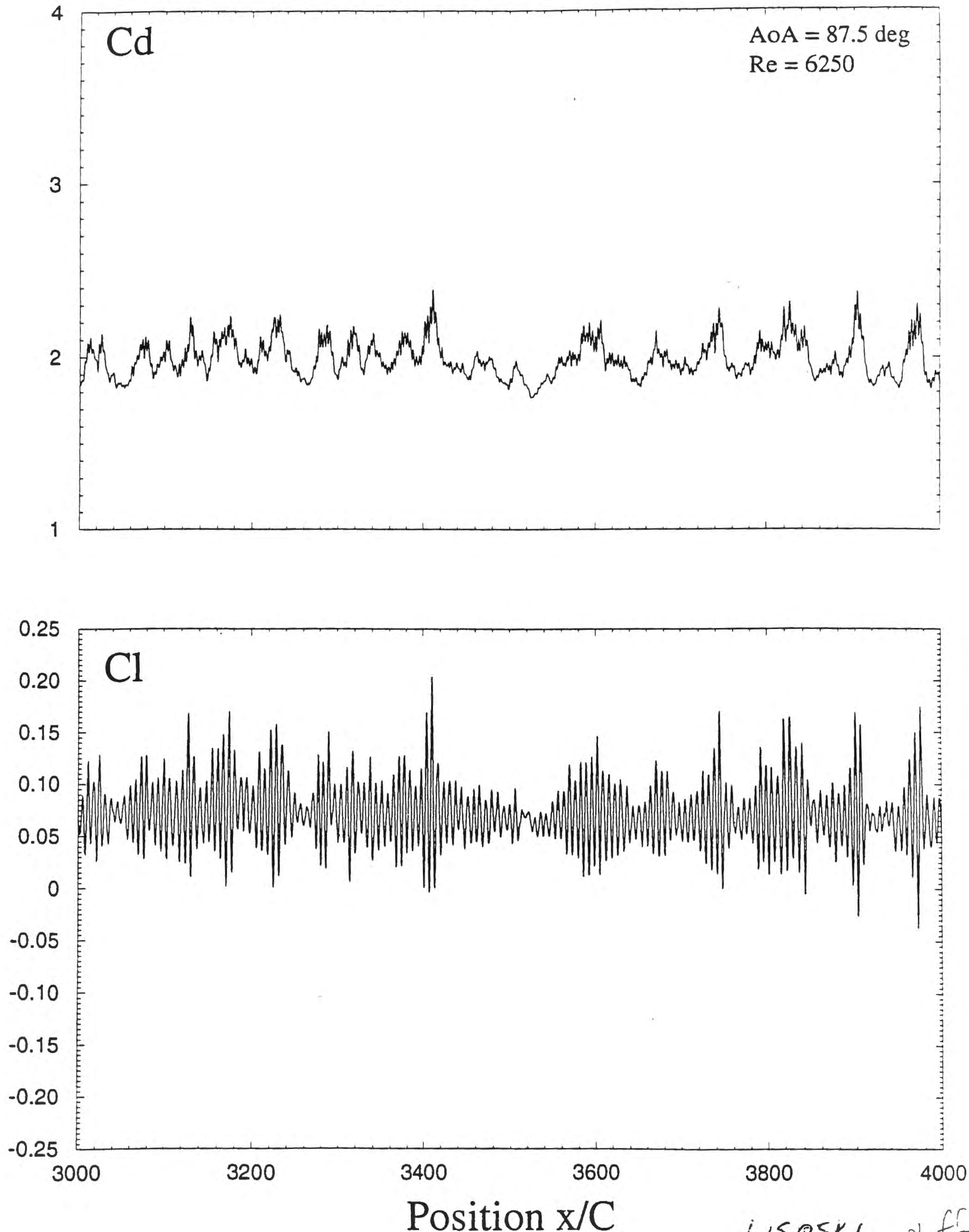

Comparison of Numerical & Experimental C_p Distributions
Front Face
Back Face (Base)
(——) Numerical Simulation;
(Δ) Fage and Johansen, 1927
C_p
y/C
-0.5
0.0
0.5
1
0
-1
-2
-3
-4
-0.5
0
0.5
y/C

Force Histories On A Normal Blunt Plate

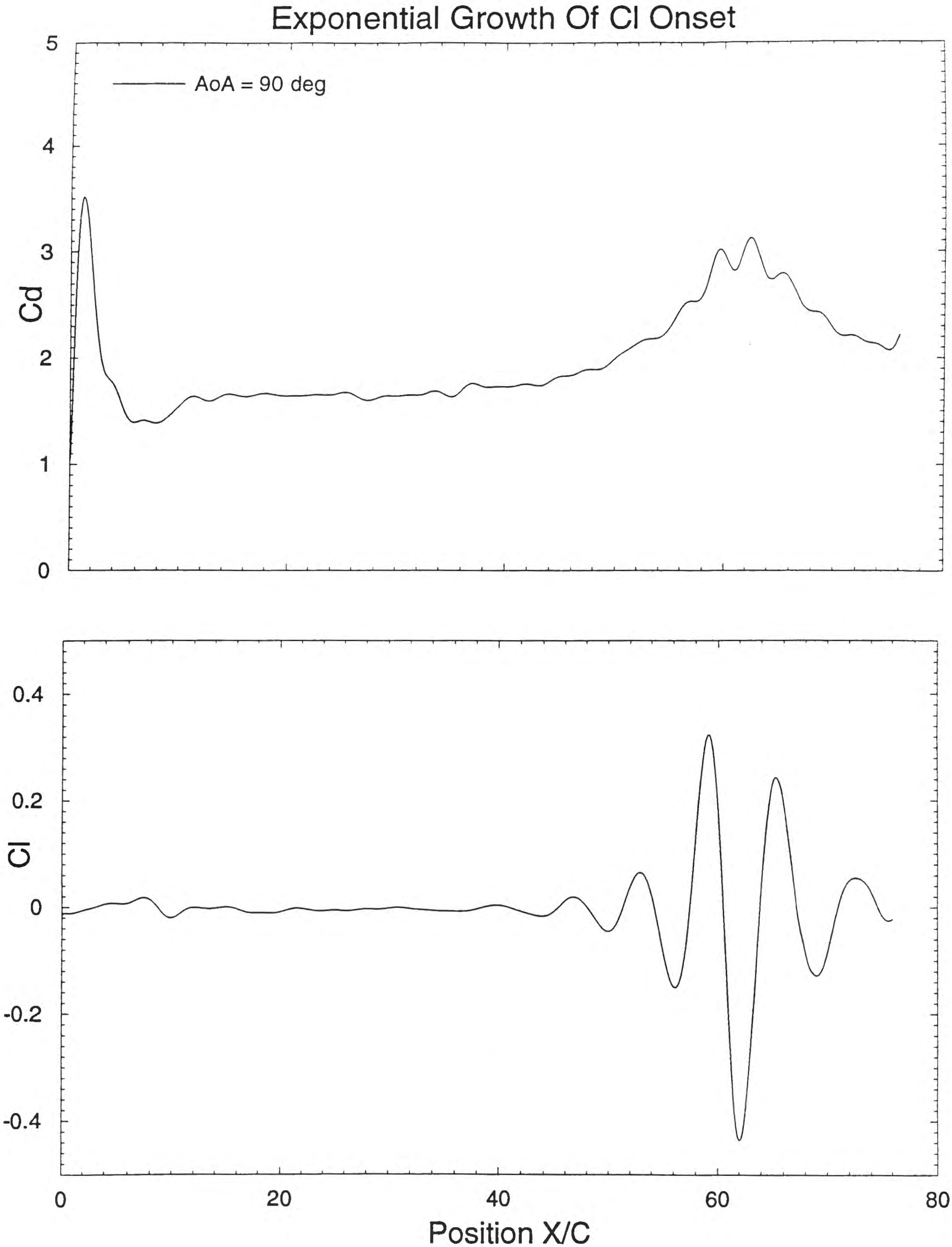


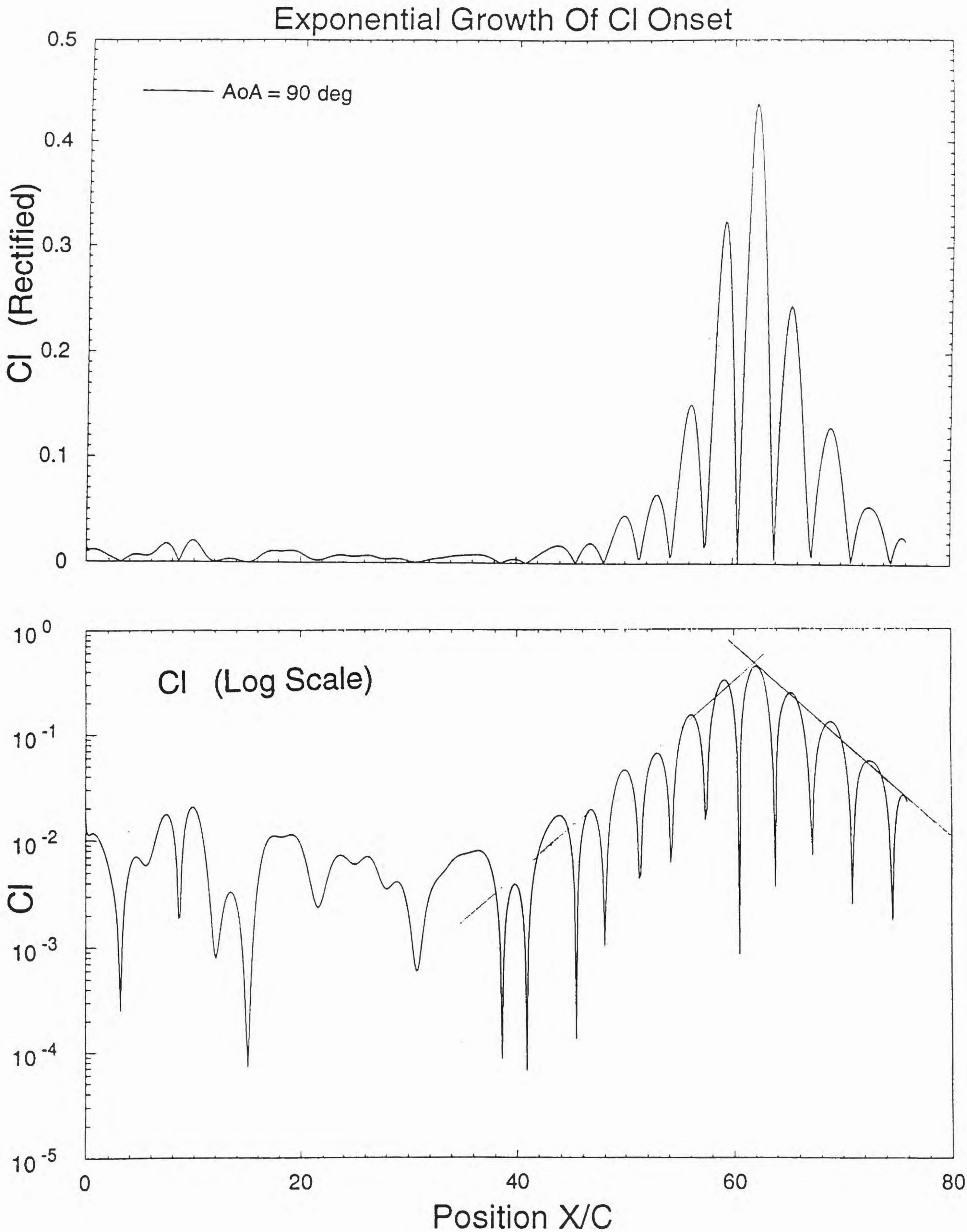
T_s ≡ Strouhal Period

Force Fluctuation - Free Surface Water Tunnel



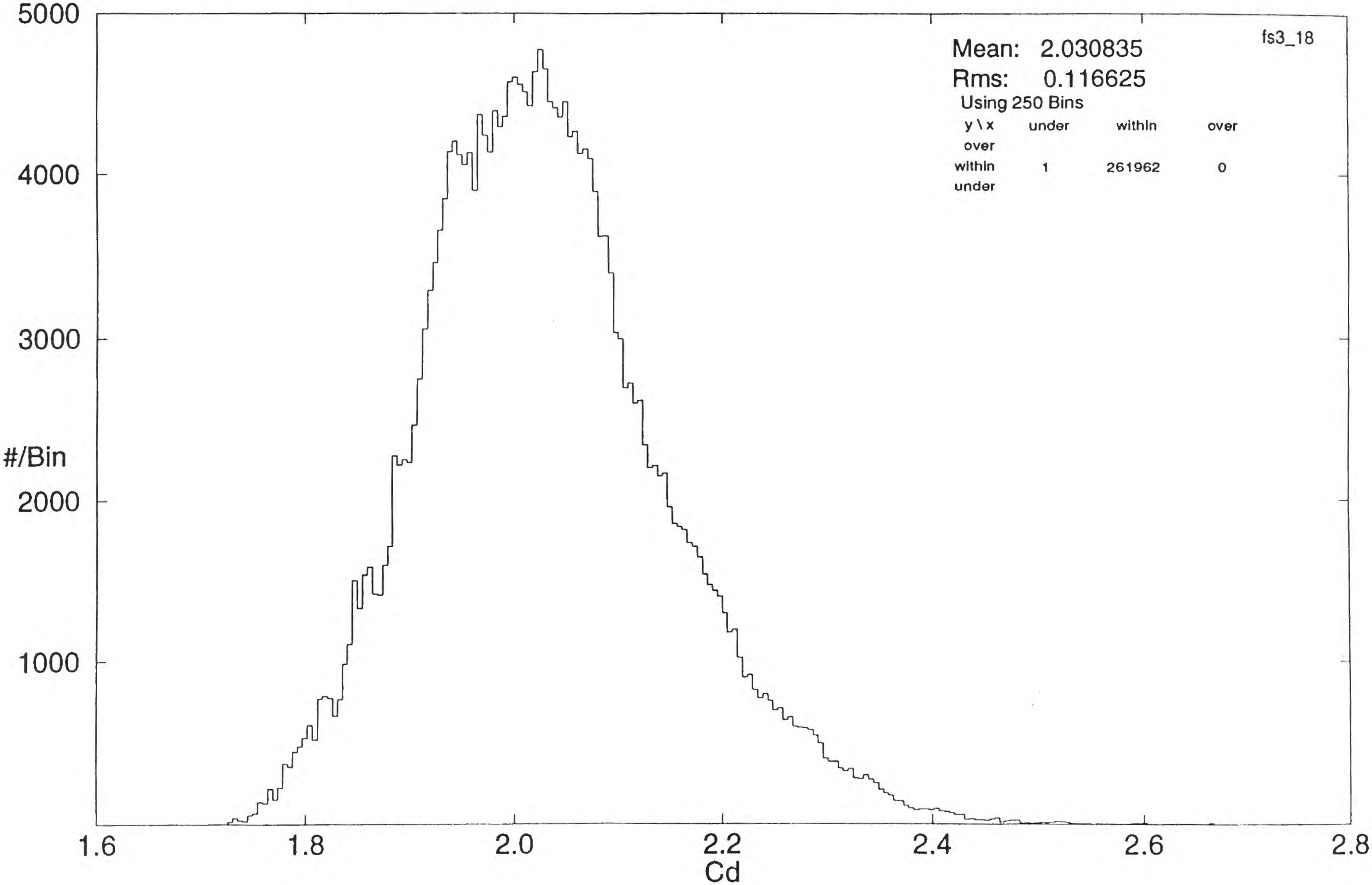
LISOSKI + FL


Exponential Growth Of Cl Onset
AoA = 90 deg
Cd
Cl
Position X/C
0
20
40
60
80
5
4
3
2
1
0
0.4
0.2
0
-0.2
-0.4

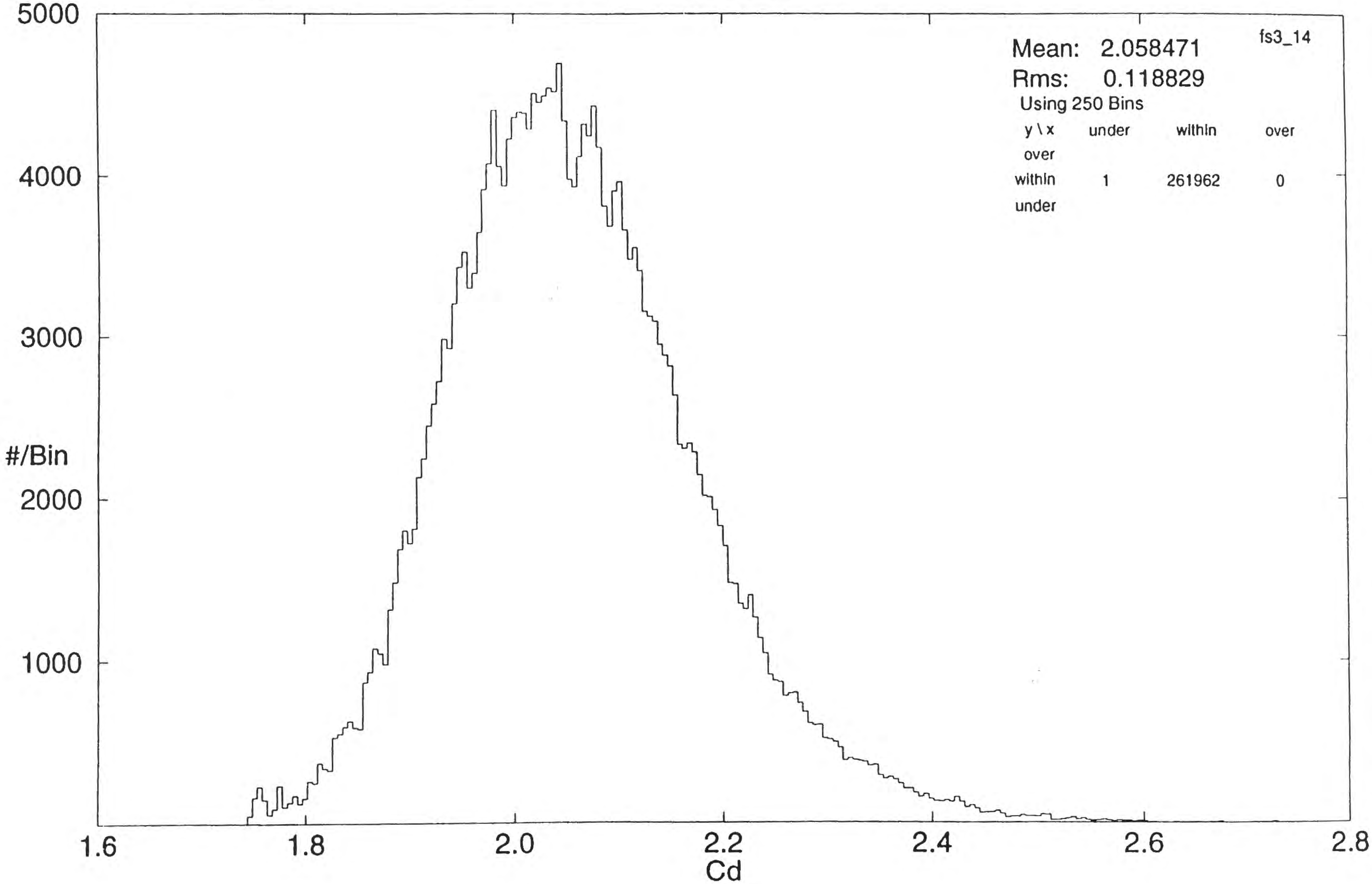


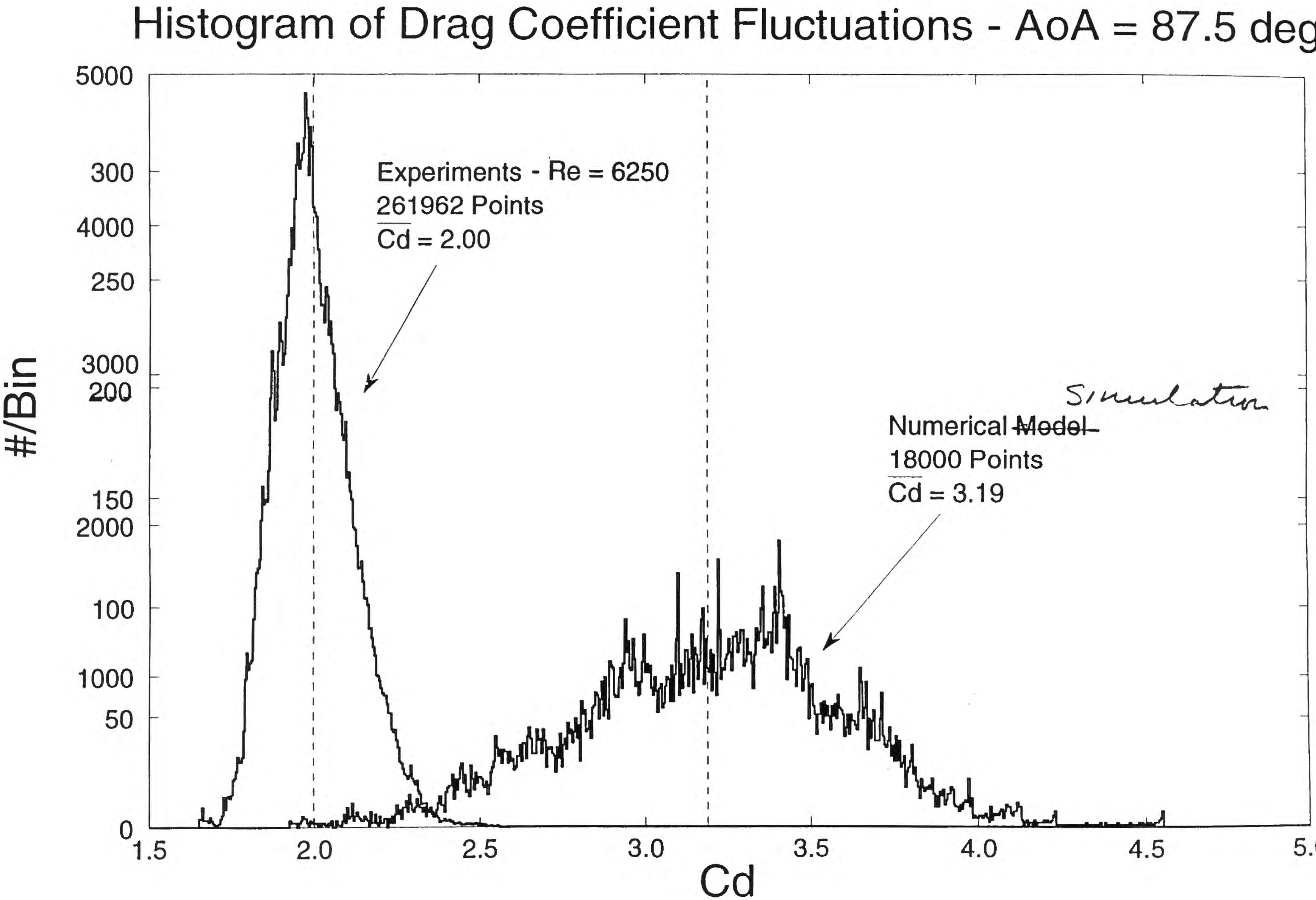
Exponential Growth Of Cl Onset
AoA = 90 deg
Cl (Rectified)
0.5
0.4
0.3
0.2
0.1
0
Cl (Log Scale)
Cl
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
0
20
40
60
80
Position X/C

Histogram of Drag Coefficient Fluctuations in FSWT — AoA = 85



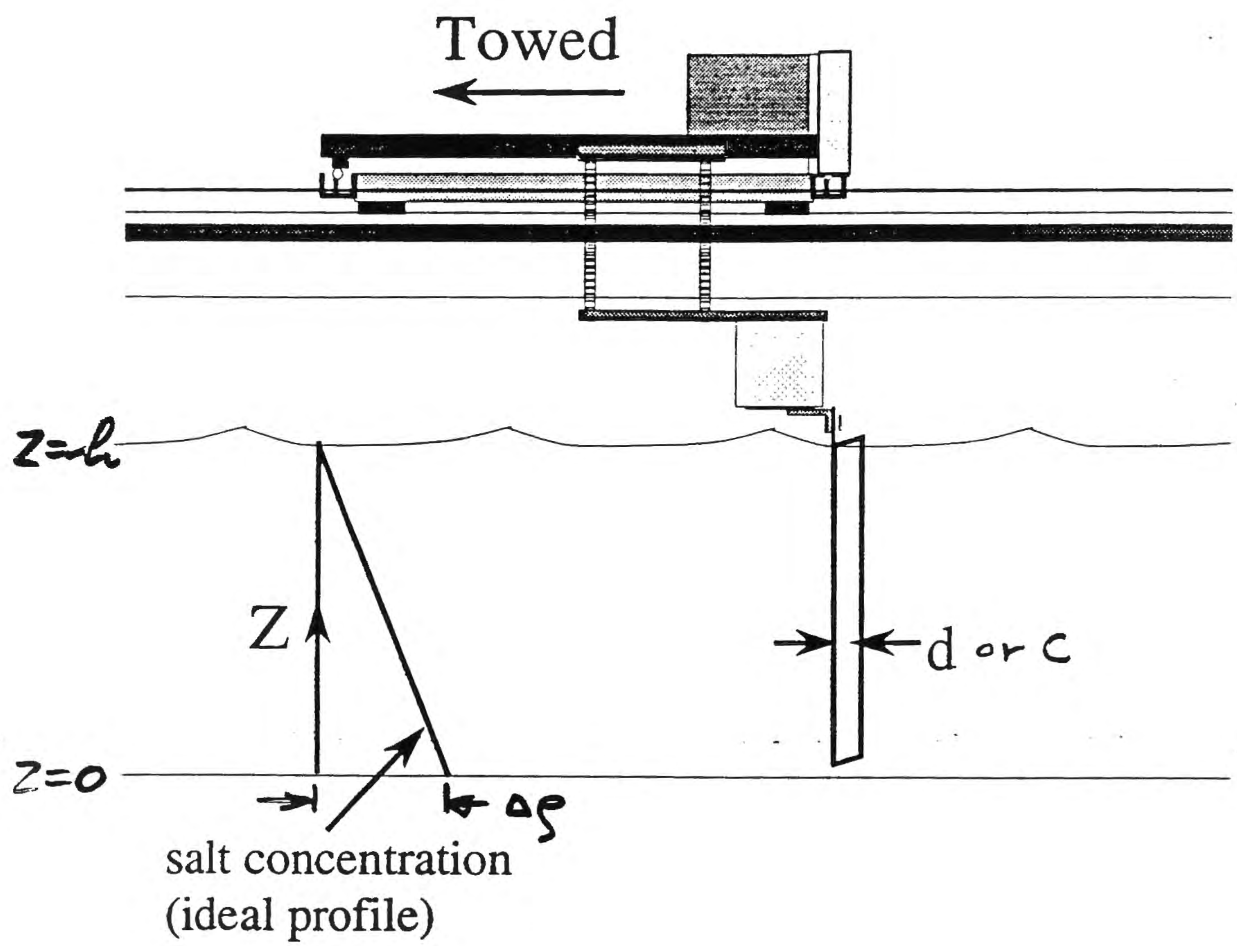
Histogram of Drag Coefficient Fluctuations in FSWT - AoA = 90




Histogram of Drag Coefficient Fluctuations - AoA = 87.5 deg
Experiments - Re = 6250
261962 Points
$\overline{Cd}$ = 2.00
Simulation
Numerical ~~Model~~
18000 Points
$\overline{Cd}$ = 3.19
#/Bin
Cd
5000
300
4000
250
3000
200
150
2000
100
1000
50
0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

Density Stratification Experiments

- reduce 3-d turbulence by damping spanwise motions.



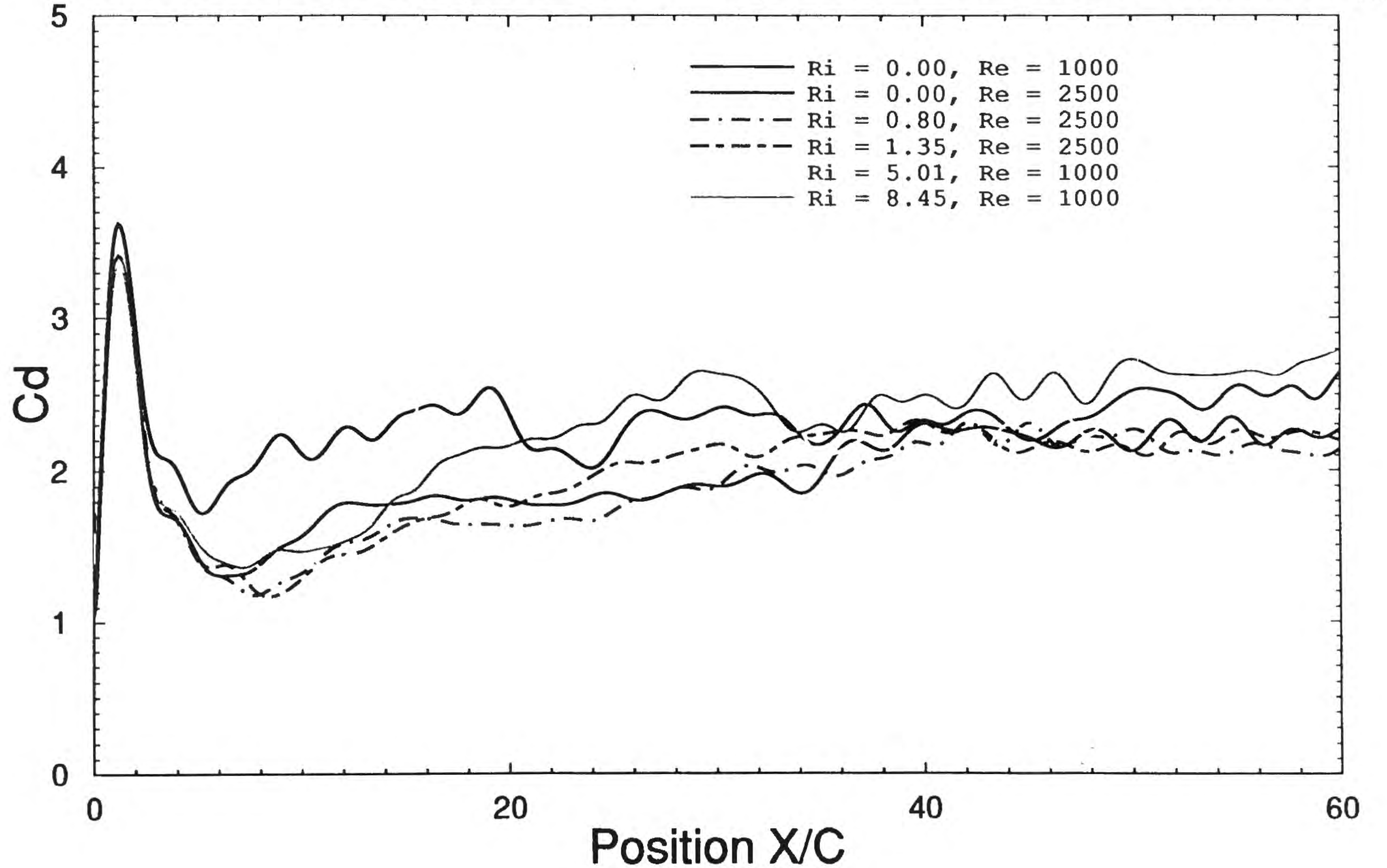
$$g\frac{d\rho}{dz} = constant \quad \text{(spanwise homogeneous)}$$

Richardson Number: measure of effect of buoyancy

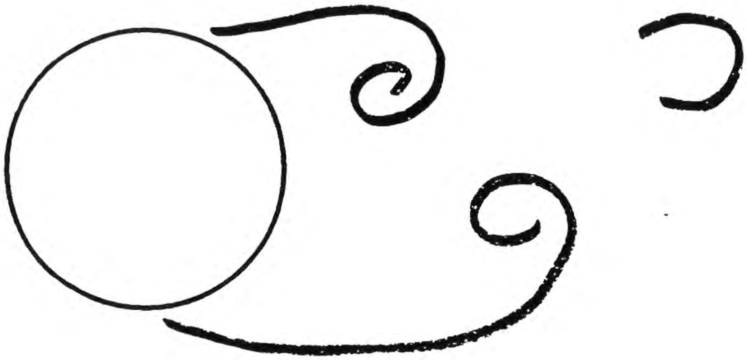
$$R_i = \frac{g\frac{d\rho}{dz}}{\rho(\frac{dw}{dz})^2} = g\frac{\frac{\Delta\rho}{h}}{\rho\frac{U^2}{d^2}} = \frac{\Delta\rho}{\rho}\frac{gd}{U^2}\frac{d}{h}$$

$$R_i = \frac{\Delta\rho}{\underline{\rho}}\frac{g}{\underline{h}}\frac{d^2}{\underline{U^2}}$$

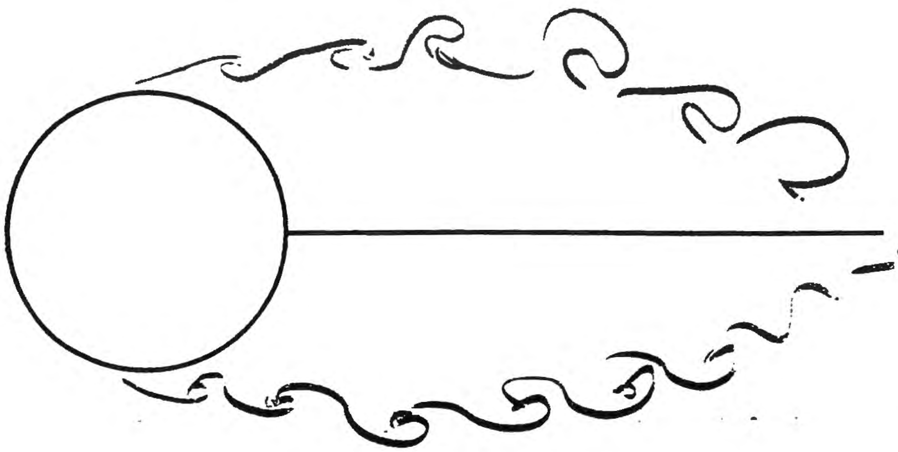
Stratification Effects (Small End Gap, C = 5cm, AoA = 90.0 deg)



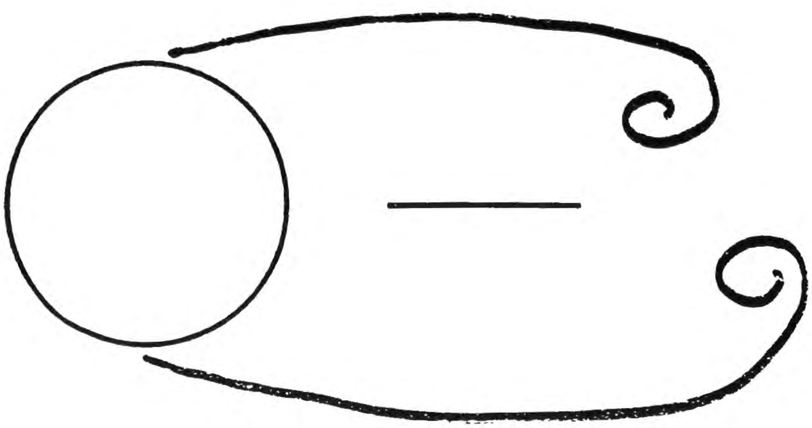
Interference Experiments
on
NEAR-WAKE DYNAMICS



Open Wake



Long
Splitter
Plate



Short
Splitter
Plate

$\boxed{\text{Splitter Screen}}$

$\sigma \equiv$ Solidity Ratio

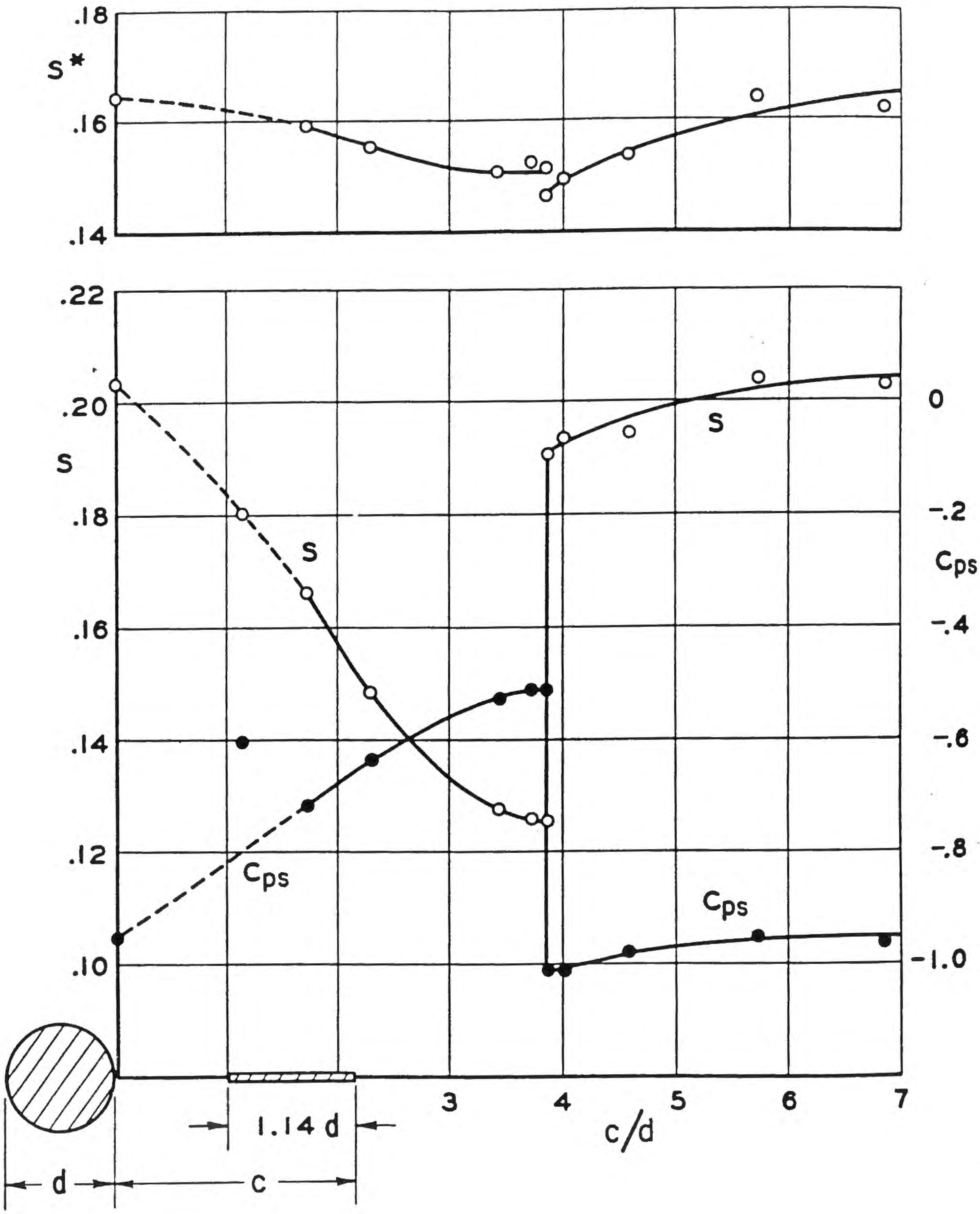
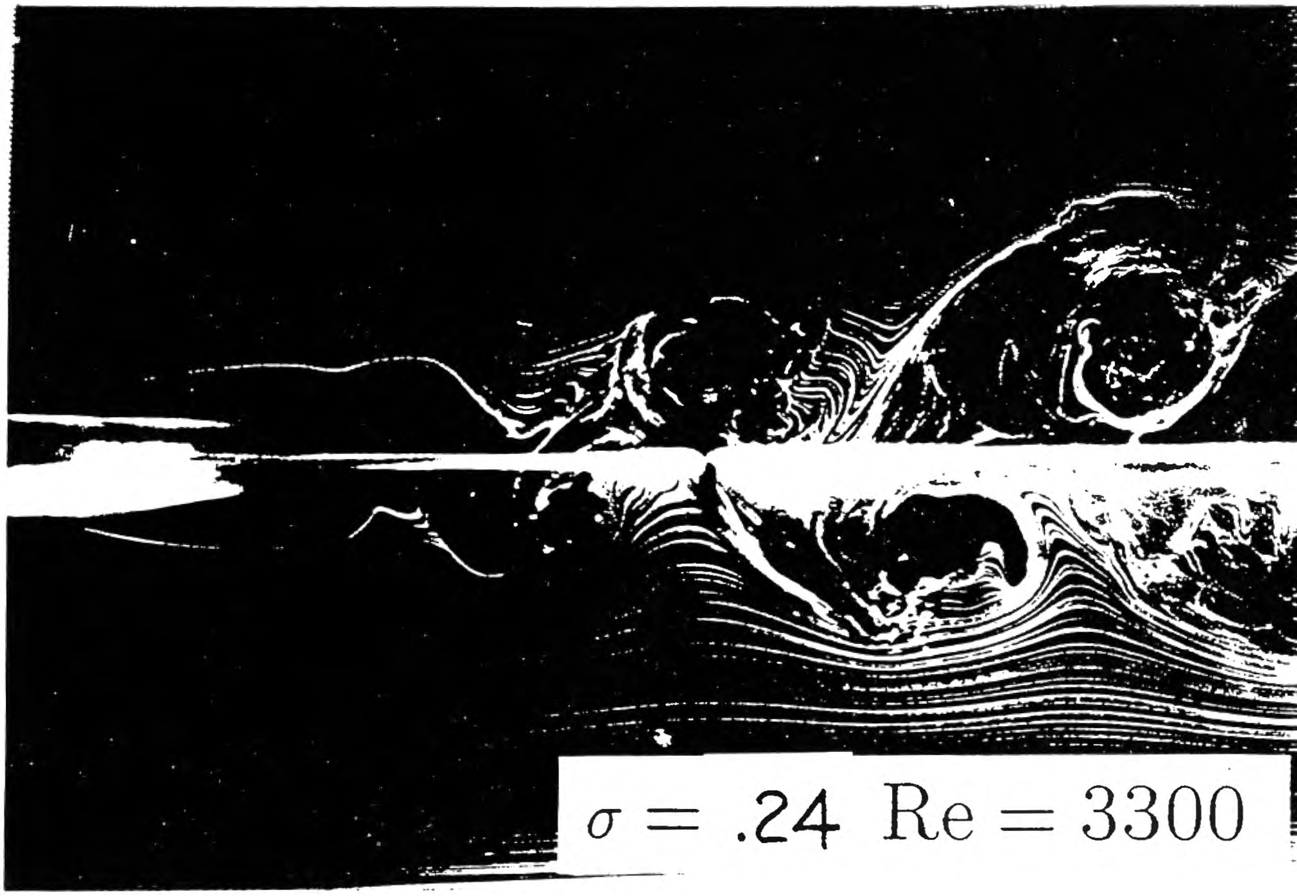
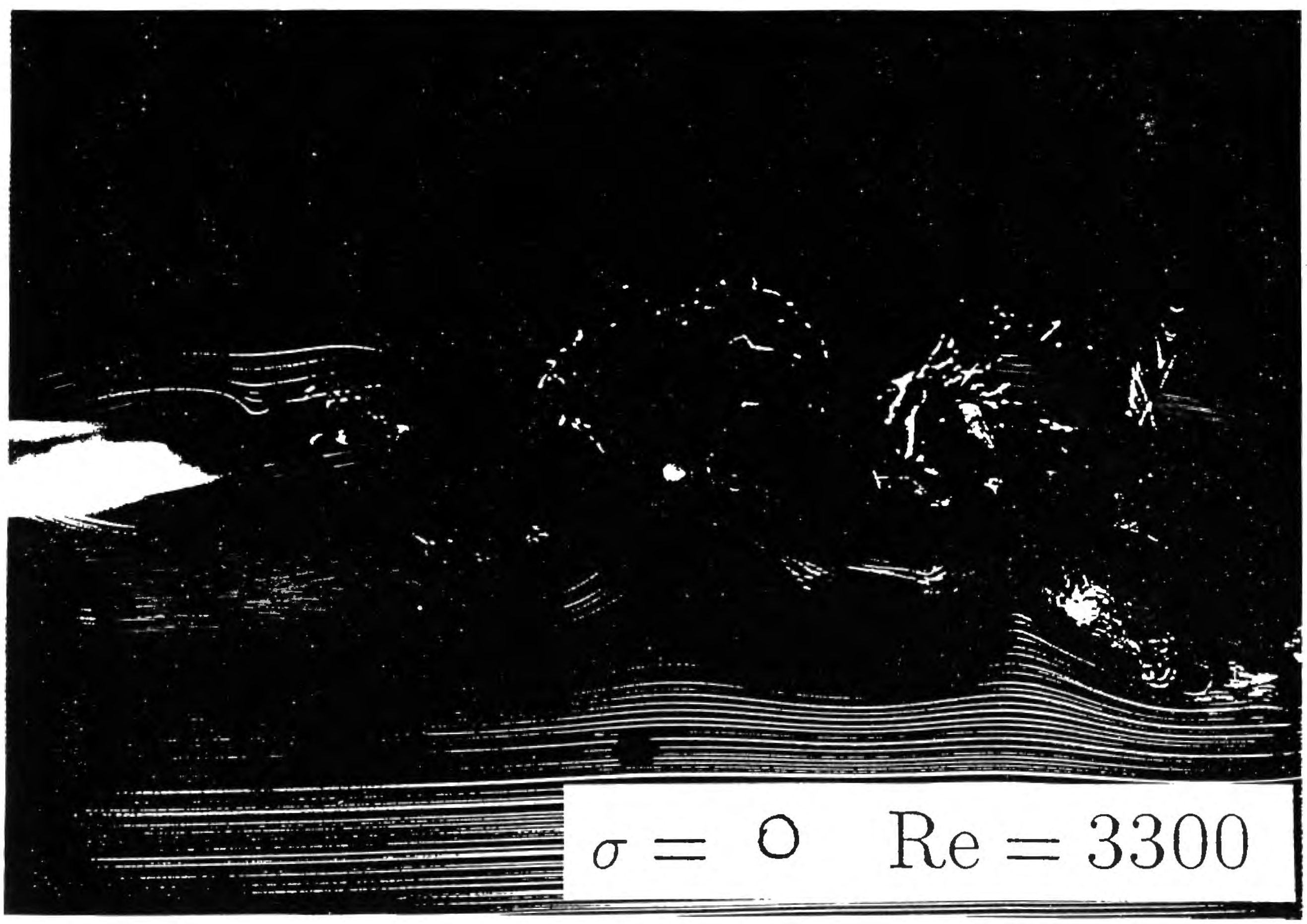
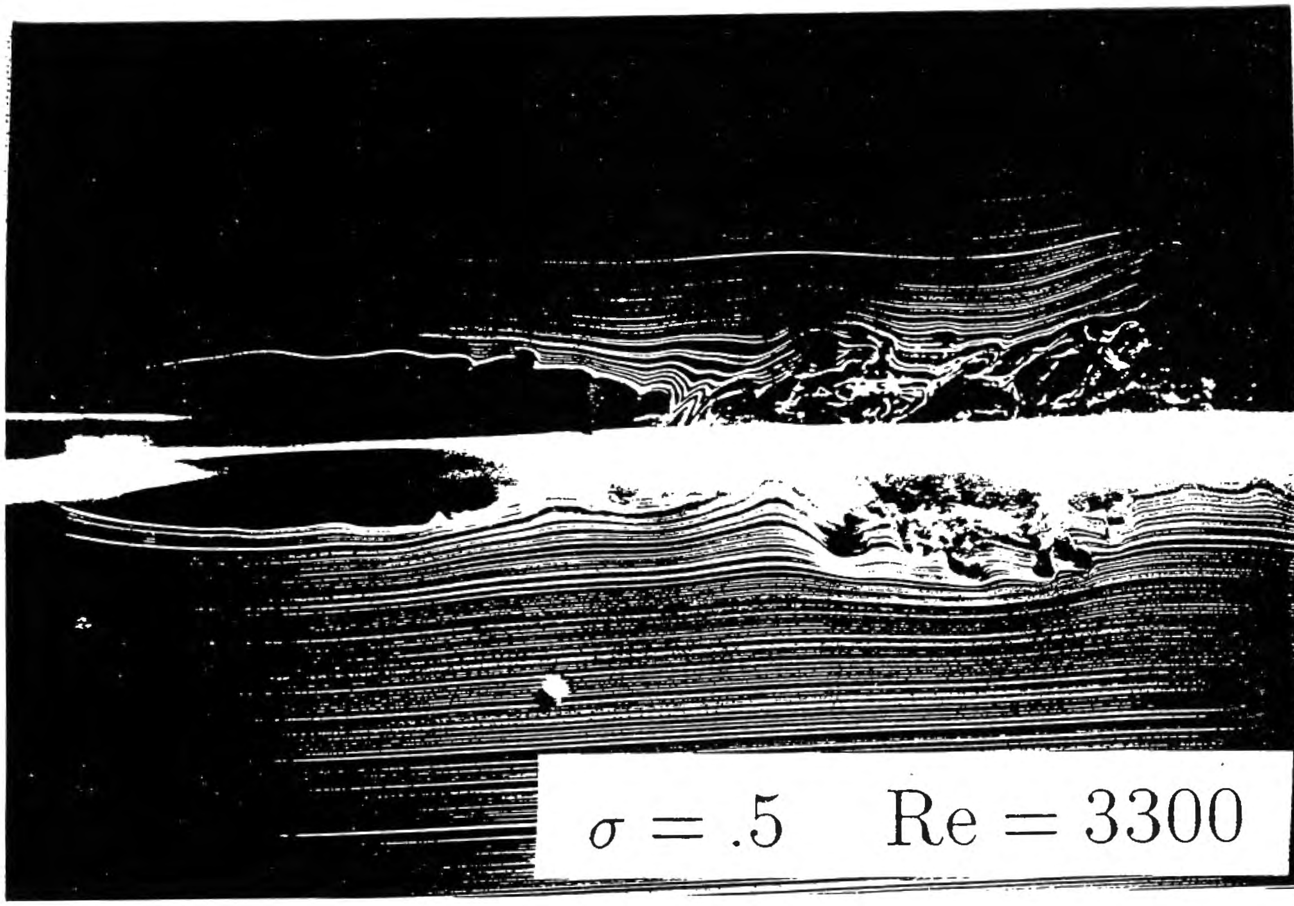


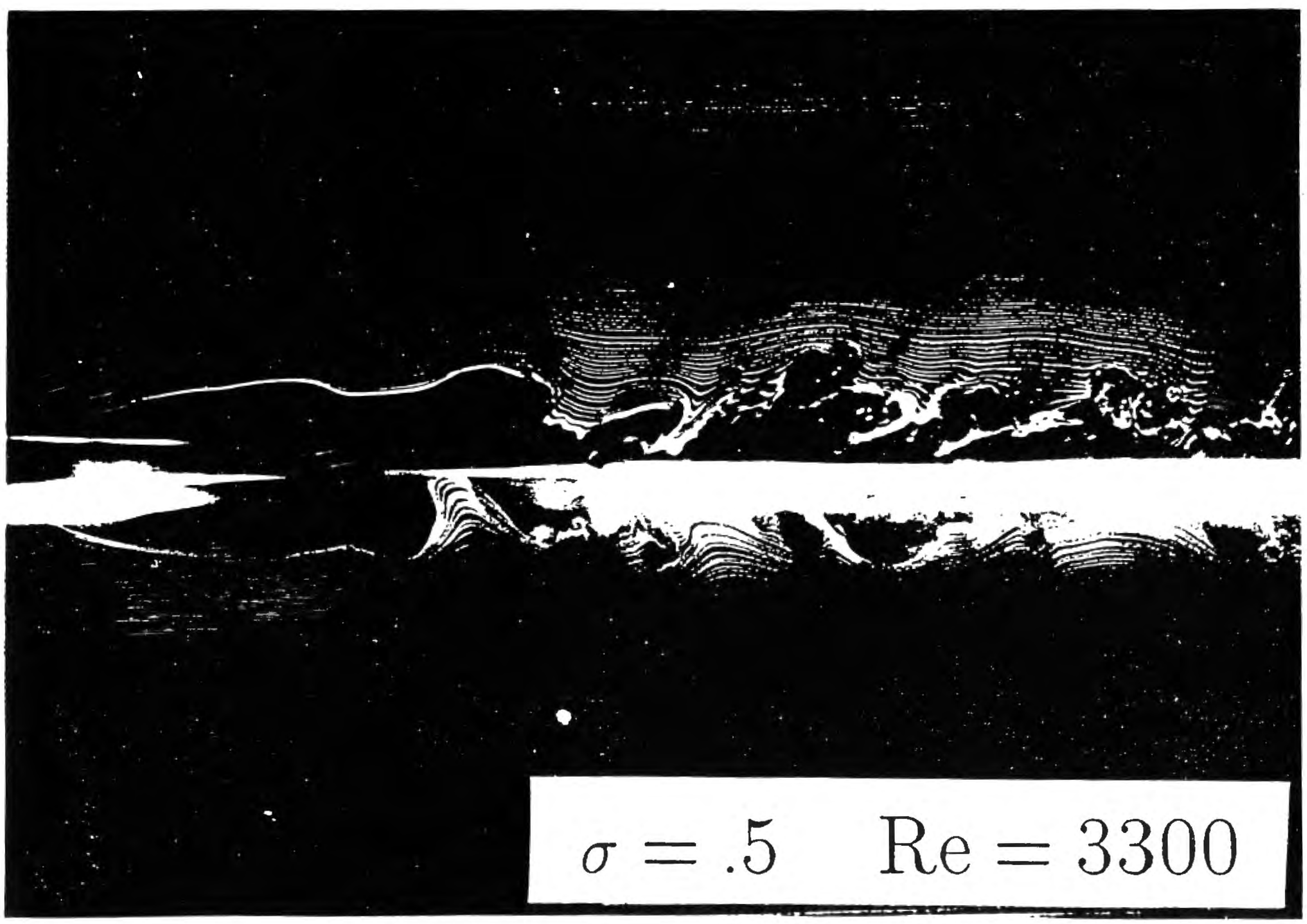
Figure 4.- Wake interference.

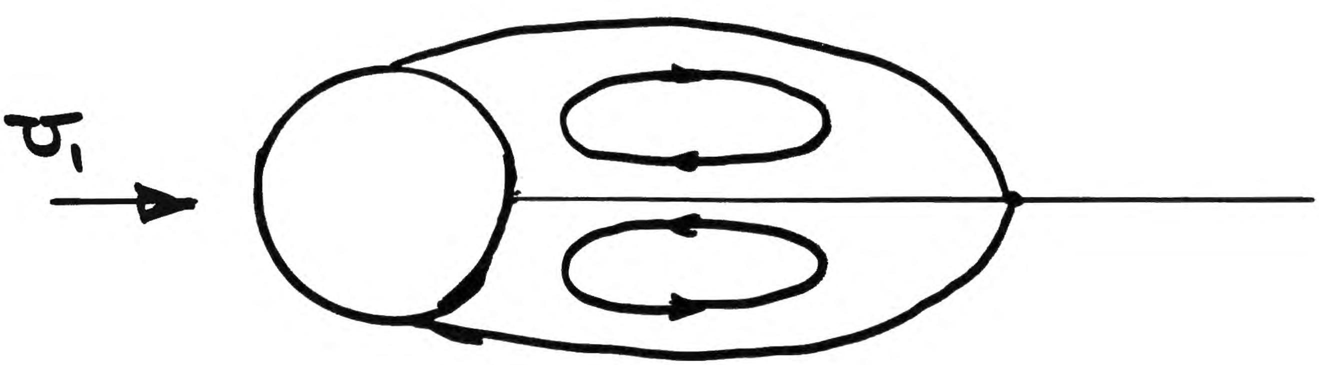
A C


$\sigma = .24 \ \mathrm{Re} = 3300$


$\sigma = 0 \quad \mathrm{Re} = 3300$


$\sigma = .5 \quad \mathrm{Re} = 3300$


$\sigma = .5 \quad \mathrm{Re} = 3300$



Mean Flow Field.

Described by Reynolds' Equations

("time-averaged

Navier-Stokes modelling")

(Effect of splitter plate?)

TURBULENT VELOCITY FIELD:

$$u_i(x_j,t) = \bar{u}_i(x_j) + u_i'(x_j,t)$$

<u>Navier-Stokes Equations</u>

continuity $\qquad \frac{\partial u_k}{\partial x_k} = 0 \qquad$ incompressible

momentum $\qquad \rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \tau_{ij}$

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

CLOSURE (Newtonian Fluid)

<u>Reynold's Averaged Equations</u> $\qquad$ ($\overline{Re}$ equations)

$$\frac{\partial \bar{u}_k}{\partial x_k} = 0$$

$$\frac{Du_i}{Dt} = \rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\bar{\tau}_{ij} + T_{ij}\right)$$

$$T_{ij} \equiv \rho\left(-\overline{u_i' u_j'}\right)$$

<u>PROBLEM OF CLOSURE</u>

TRADITIONAL METHODS : (velocity field)

- Reynolds-averaged ($\overline{Re}$) modelling

  \- Shear Flows -

one-point correlations, e.g. $\overline{u'v'}$, $\overline{u'p'}$, etc.

- Statistical Theory

  \- Homogeneous Flows -

two-point correlation functions, e.g.

$$\overline{u'(x,t)\, u'(x+r,\, t+\tau)} = f(r,\tau)\, \overline{u'^2}$$

spectra

MODERN APPROACH : (vorticity field)

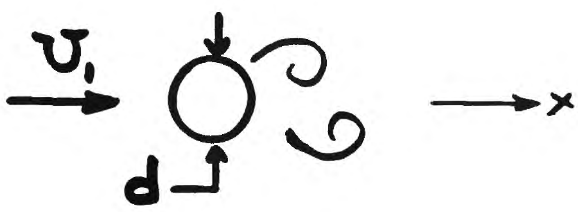
Incorporate

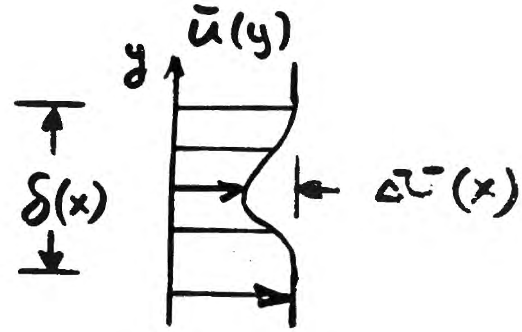
- Describe "organized", "coherent" vortical structures and their interactions <u>before</u> doing the statistics.

How? What are they doing? : They are a manifestation of the [illegible]

Near & Far Fields of Free Shear Flows

Cylinder Wake





"**Near Wake**" ($x \leq 5d$)

Wake Oscillation, Vortex "Shedding".

Initial, fixed scales

U_1, d

$f_K = 0.2 \frac{U_1}{d}$

sharp spectrum

Primary Instability:

"Absolute"

Fixed

"**Far Wake**" ($x \gtrsim 50d$)

Evolving Scales

$\Delta U(x)$, $\delta(x)$

$f_m(x) \sim 0.2\, U_1/\delta(x)$

broad spectrum

"Fully developed turbulence"

Primary Instability:

"Convective"

Intermittent

* (wave packet.

IMPLICATIONS AND USES OF COHERENT STRUCTURES

(ideas not accessible from traditional approaches)

- Role of global (primary) instability

  characteristic for each shear flow

  (implications for universal $\overline{Re}$ models?)

- Rational explanation and correlation of parametric effects:

  velocity ratio U_2/U_1

  density ratio ρ_2/ρ_1

  compressibility M_1, M_2

  entrainment parameters

- Sensitivity to perturbation (Wygnanski and Oster)

  uniqueness

  self-excitation? (Corcos and Kaul)

- Controllability

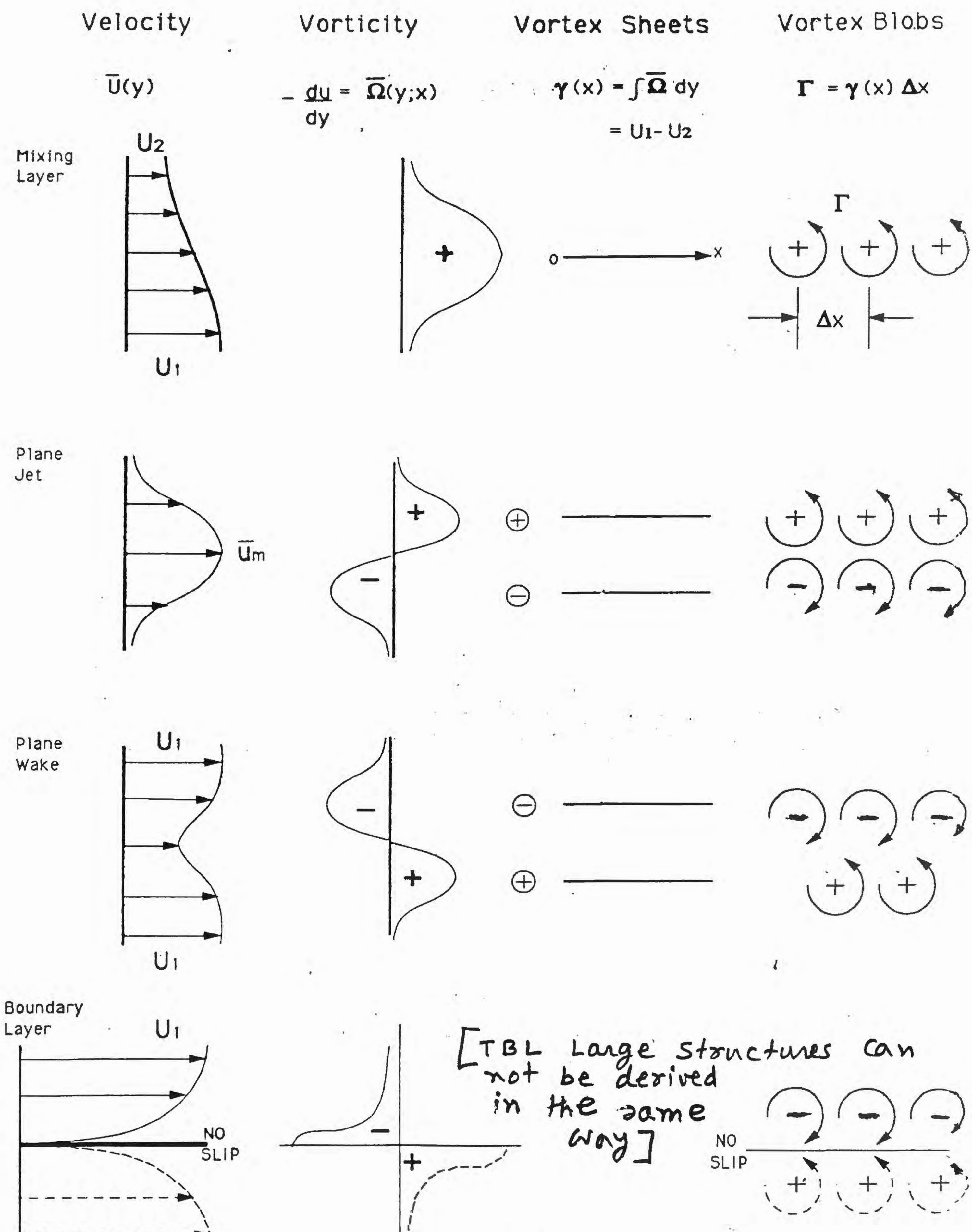
- Lagrangian view useful or necessary

  e.g. coherent structure as a stirred reactor

  (Broadwell)

- Closed models (Morris, Liu)

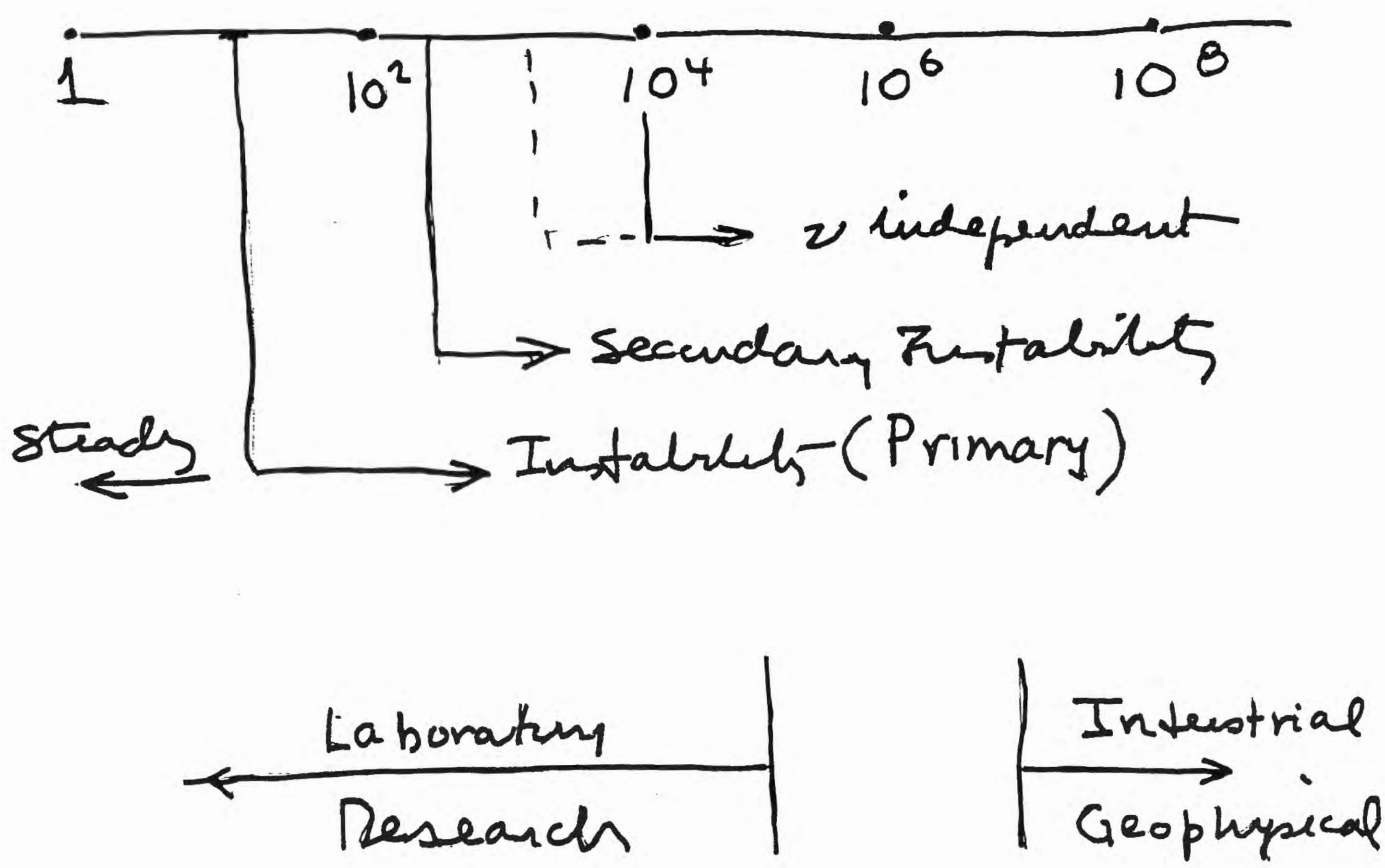
  with $\rho u'v'$ from instability equations



[TBL Large structures can not be derived in the same way]

Reynolds-Number Regimes for Free Shear Flows

$$Re \equiv \frac{UL}{\nu}$$



APPENDIX
INFORMATION ON SEMINAR SPEAKERS

ABBREVIATED VITAE

FAZLE HUSSAIN — CITIZENSHIP United States

EDUCATION	Ph.D. (1969) & M.S. (1966) Stanford U.; B.S. (1963) Bangladesh U. (all in Mech. Engr.)
MEMBERSHIPS	Fellow ('85), APS ; Fellow ('87), ASME; Associate Fellow ('76), AIAA
PROFESSIONAL EXPERIENCE	1989 - Cullen Distinguished Professor, U. of Houston (UH) 1985 - 89 Distinguished University Professor, UH 1976 - Professor, Mech. Engr. Dept., UH 1973 - 76 Assoc. Prof., Mech. Engr. Dept., UH 1971 - 73 Asst. Prof., Mech. Engr. Dept., UH 1969 - 71 Visiting Asst. Prof., Dept. of Mechanics, The Johns Hopkins U. Director, Institute for Fluid Dynamics and Turbulence, UH (1991 -)
TECHNICAL EXPERTISE	Turbulence, vortex dynamics, aerodynamics, combustion, hydrodynamic stability, chaos, aeroacoustics, measurement techniques
CONSULTING	NASA-Langley, NASA-Ames, Lockheed-Georgia, Southwestern Labs, Stauffer Chem. Co, NL Industries, Flow Industries, Spectron Labs, Inst. of Comp. Fluid Dyn.(Tokyo)
EDITORSHIPS	Associate Editor, *The Physics of Fluids*, American Institute of Physics (1981-84) Assistant Editor, *Turbulence in Liquids*, 1975 - 1983 Biennial Volumes, Science Press Editorial Advisory Board, *Experimental Thermal and Fluid Science*, Elsevier Press (1988 -)
BOOK	*Nonlinear Dynamics of Structures*, 1991 (eds. Sagdeev, Frisch, Hussain, Moiseev & Erokhin), World Scientific
SOME PANELS/ SCIENTIFIC COMMITTEES	Advisory Committee, NASA-Stanford Center for Turbulence Research (1988 - 91) Advisory Board, Institute of Computational Fluid Dynamics (Tokyo) Advisory Board, *3rd*(1981) through *8th*(1991) *Symposia on Turbulent Shear Flows* Organizing Committee, *Biennial Symposia of Turbulence*, U. of Missouri-Rolla, (1975 -) Organizing and Scientific Committee, *Beer-Sheva International Seminar on MHD and Turbulence*, Israel,(1985 -) Vice-Chairman, *Int. Symp. on Generation of Large Structures in Continuous Media*, Perm - Moscow, June 11-20 (1990) Technical Committee on Turbulence, ASCE (1987 - 91) Asian Fluid Mechanics Committee (1979 -) Scientific Committee, *Int. Symp. on Transport Phenomena* U. of Tokyo (1987) Scientific Committee, *IUTAM Symposium on Topological Fluid Mech.* Cambridge U.(1989) Fluid Dynamics Prize Committee, APS (1991 -) Scientific Committee, *IUTAM Syposium on Eddy Structure Identification in Free Turbulent Shear Flows*. Poitiers, France (1992)
RESEARCH AWARDS	*Eckhart Prize* (for outstanding Ph.D. Thesis), Stanford University, (awarded in 1971) *Senior Research Excellence Award*, Cullen College of Engineering, UH, 1979 *Exchange Scholar:* 1980 (India), 1983 (China) *1984 Freeman Scholar*, (biennial award of ASME) *Senior Research Excellence Award*, UH, (first recepient) 1985
RESEARCH ACTIVITY SUMMARY	129 Archival papers 69 Conference proceedings papers 115 Oral presentations at major conferences (exclusive of invited lectures) 55 Invited lectures at international meetings (including keynote lectures) Invited seminars (over 150 in USA and abroad) 59 Competitive research grants

STEVEN A. ORSZAG

Steven A. Orszag is the Hamrick Professor of Engineering and Director and Professor of Applied and Computational Mathematics at Princeton University. He studied at M.I.T. and Cambridge University prior to receiving his Ph.D. in Astrophysics from Princeton in 1966. After a year at the Institute for Advanced Study, he returned to M.I.T. where he was Professor of Applied Mathematics until assuming his present position in 1984. His research interests include numerical analysis, applied mathematics, and fluid dynamics. His major contributions include the development of spectral numerical methods, the theoretical analysis of the mechanism of transition in shear flows, the first numerical simulations of three-dimensional turbulent flows, and the development of dynamic renormalization group methods for turbulence. His recent awards include the 1986 AIAA Fluids and Plasmadynamics Award, a Guggenheim Fellowship, and the 1991 Otto Laporte Award of the American Physical Society. Prof. Orszag is Editor-in-Chief of the Journal of Scientific Computing, Amer. Inst. of Physics Series in Computational Physics, and Springer Series in Computational Physics. He has written over 250 papers and 9 books. He is co-author with Carl M. Bender of the widely used Advanced Mathematical Methods for Scientists and Engineers and the forthcoming Partial Differential Equations for Scientists and Engineers.

DANIEL M. NOSENCHUCK

[redacted]

PII Redacted

(office): (609)258-5136

EDUCATION

Ph.D. California Institute of Technology, Pasadena, California
Aeronautics, Thesis Advisor: H.W. Liepmann / June 1982

M.S. California Institute of Technology, Aeronautics / June 1977

B.S. Syracuse University, Syracuse New York
Aeronautical and Mechanical Engineering, cum laude / May 1976

EXPERIENCE

7/88 - Present Associate Professor of Mechanical and Aerospace Engineering
8/83 - 6/88 Assistant Professor
Princeton University, Princeton New Jersey

Teach graduate and undergraduate courses in fluid mechanics.
Current research areas:

1) development and application of the Navier-Stokes Computer
2) experimental and numerical fluid mechanics:
   control of complex turbulent and vortical flows

HONORS

- Presidential Young Investigator Award (NSF), 1984-1989
- GTE Emerging Scholar, 1987
- Rheinstine Award, School of Engineering, Princeton University, 1986
- IBM Faculty Development Award 1984 - 1985
- EMMY Award from the Academy of Television Arts and Sciences for Outstanding Individual Achievement - Special Visual Effects: '*The Day After*,' 1984
- The William F. Ballhaus Prize, for an 'Outstanding Doctoral Dissertation in Aeronautics,' California Institute of Technology, 1982
- Graduate Fellowships, California Institute of Technology, 1976

MISCELLANEOUS

Patents:

U.S. Patent No. 4811214 (March 1989): 'Dynamic Reconfiguration System for Pipelined Computers', Numerous foreign patents also awarded.

U.S. Patent Pending: 'A Parameterized Optimizing Compiler'

Reviewer for:

- AIAA Journal
- Journal of Fluid Mechanics
- Physics of Fluids
- Review of Scientific Instruments

Department of Defense Activities:

- Member of Defense Science Board Ballistic Missile Defense Task Force
- Member of Defense Science Study Group

Consultant to:

- Defense Science Board, Washington DC
- DSV Partners, Princeton, NJ
- Institute for Defense Analysis, Alexandria VA
- Northwest Research Associates Inc., Belleview WA
- Praxis Film Works, North Hollywood, CA
- Union Camp Corporation, Lawrenceville, NJ

Transferred Navier-Stokes Computer technology from Princeton University to Concurrent Computer Corporation, Tinton Falls, NJ, in 1987, and Supercomputer Solutions Inc, San Diego, CA., in 1989.

DANIEL M. NOSENCHUCK

Associate Professor

Daniel M. Nosenchuck's research interests include experimental and computational fluid mechanics, dynamic flow visualization, and advanced supercomputer architectures. His major contributions include experimental active laminar-flow control, the first successful demonstration of active turbulence control, and the development of a parallel-processing supercomputer. He was a charter-year recipient of the five-year NSF Presidential young Investigator Award (1984-89). He also received of the IBM Faculty Development Award (1984-85) and the Princeton University School of Engineering Rhinestein Award (1986) for work related to the implementation of unique flow fields, and the development of new flow visualization techniques. He received the National EMMY Award in 1984 for Outstanding Individual Achievement in Special Visual Effects. He is active in industrial consulting and also consults directly with the Department of Defense, and is a member of DoD Defense Science Board Task Forces.

The underlying theme of his work revolves around the control of complex fluid flows. To achieve this, he is currently engaged in several areas of research. These include the study and experimental active control of turbulent boundary-layers in a low-speed water channel, wake-vortex prediction and control, the development of a new three-dimensional dynamic flow-visualization technique, and the design and construction of a very-high-speed computer for use in complex flow simulations and control applications.

Experimental Fluid Mechanics

The goal of this research is to reduce skin-friction drag by modifying turbulent boundary layers. A new technique using a wall-normal electromagnetic body force to directly suppress near-wall turbulent instabilities is in the early stages of development. Preliminary experimental results indicate the possibility of dramatic reductions in turbulence and wall-shear with little power expenditure. Other experiments involve arrays of thin-film, sensors and actuators coupled to high-speed feedback-control electronics. With appropriate special-purpose electronics, a significant attenuation of boundary-layer instabilities has been realized. A second major area of investigation is the mitigation of the wake-vortex hazard produced behind large aircraft, and the alleviation of trailing vortices behind submarines. This is being investigated using a new approach to induce instabilities in the vortex sheet produced by lifting surfaces. Through the development and application of an optimizing numerical design and flow simulation procedure, small modifications to the lifting surface geometry were predicted to modify substantially the trailing vortex. Preliminary experiments were used to validate the predictions.

To understand these complex, nonsteady boundary-layer and vortex flows, a new diagnostic technique was developed within the lab. A laser-sheet is rapidly scanned through flow-fields into which a laser-fluorescing dye has been added, and a series of two-dimensional images are obtained. A single scan is comprised of many closely-spaced sheets. From this space-filling data set, a three-dimensional flow visualization image, representative of one instant in the flow, is obtained. Repeated scanning is used to create a complete three-dimensional nonsteady qualitative record of the flow. He is currently extending the technique to encompass quantitative methods, and investigating its use as a real-time input sensor for active control experiments.

Navier-Stokes Computer

Problems in fluid mechanics involving complex flow simulations require far more speed and capacity than that provided by current and proposed conventional and parallel supercomputers. To address this concern, the Navier-Stokes Computer (NSC) was developed. The NSC is a fully general-purpose parallel-processing machine, comprised of individual Nodes, each comparable in performance to current supercomputers. The projected speed and capacity of a 128-Node NSC is many orders-of-magnitude greater than that of existing supercomputers. New architectural features have provided the capability to efficiently address a far greater range of problems than possible on conventional machines. The first large-scale applications of the NSC involved the simulation of complex flows at moderate Reynolds-numbers, including nonsteady flows with separation over a large domain. A fast optimizing NSC FORTRAN compiler, which uses a new 'approximate simulation' technique coupled is in development.

Selected Publications

"The Direct Control of Wall Shear Stress in a Turbulent Boundary Layer," (with G.L.Brown), submitted to Phys. Rev. Lett., 1992.

"Parameterized Memory/Processor Optimizing FORTRAN Compiler for Parallel Computers," To be published in Proceedings of 1992 Scalable High Performance Computing Conference, IEEE Computer Society Press.

"Control of Wingtip Vortices," (with W.S. Flannery and G.L. Brown) Proceedings of FAA Wake Vortex Symposium, Washington, DC, 29-31 October 1991.

"The Navier-Stokes Computer," Special-Purpose Computers, (with W.S. Flannery and E. Hayder) B. Alder, ed., pp 97 - 134, 1988.

"Active Control of Sublayer Disturbances Using an Array of Heating Elements," (with M. K. Lynch and J. P. Stratton) Proc. 2nd ASME/JSME Thermal Engineering Joint Conf., 1987.

"Three-Dimensional Flow Visualization Using Laser-Sheet Scanning," (with M. K. Lynch). Proceedings of the AGARD Conference on Aerodynamic and Related Hydrodynamic Studies Using Water Facilities, AGARD Conference Preprint No. 413, pp 18-1 - 13, 1986.

"Active Control of Laminar-Turbulent Transition," (with H.W. Liepmann). J. Fluid Mech. Vol 118, pp 201-204, 1982.

GARRY L. BROWN
Professor and Chairman

Garry L. Brown was appointed Chairman of the Department of Mechanical & Aerospace Engineering at Princeton University in July, 1990. He arrived at Princeton after 9 years as Director of the Aeronautical Research Laboratory, Department of Defense, Melbourne, Australia. Prior to that he was a Professor of Aeronautics at the Graduate Aeronautical Laboratories at California Institute of Technology and a senior reader and lecturer in Mechanical Engineering at the University of Adelaide, Australia. Prof. Brown has published widely in the field of turbulence and more recently on vortex breakdown. His work with Prof. Roshko which reported the discovery of coherent structure in turbulent mixing layers has been recognized by the Journal of Fluid Mechanics as a "classic paper." His work with Wallace (at Adelaide University) and subsequently with Mungal (at CalTech) developed a new way of conducting combustion experiments at high Reynolds numbers in highly reactive gases. His collaboration with Liepmann and Nosenchuck on the control of boundary layer transition has been recognized as an important result in the development of turbulence control. Recent work with Lopez (at the Aeronautical Research Laboratories) on the classic problem of axisymmetric vortex breakdown has led to a new necessary criterion for vortex breakdown based on the development of negative azimuthal vorticity. Prof. Brown is continuing his work on vortex dynamics, turbulence and compressible gas dynamics in collaboration with other members of the department.

Sample Publications:

1. G.L. Brown and A. Roshko, "On Density Effects and Large Structure in Turbulent Mixing Layers," *J. Fluid Mech.* **64**, pp. 775-816 (1974).

2. P.E. Dimotakis and G.L. Brown, "The Mixing Layer at High Reynolds Number: Large Structure Dynamics and Entrainment," *J. Fluid Mech.* **78**, pp. 535-560 (1976).

3. G.L. Brown and Andrew S.W. Thomas, "Large Structure in a Turbulent Boundary Layer," *Phys. Fluids*, **20**, No. 10, Pt. II, pp. 243-252 (1977).

4. H.W. Liepmann, G.L. Brown, and D.M. Nosenchuck, "Control of Laminar-Instability Waves Using a New Technique," *J. Fluid Mech.* **118**, pp. 187-200 (1982).

5. G.L. Brown and J.M. Lopez, "Axisymmetric vortex breakdown, Part 2. Physical mechanisms," *J. Fluid Mech.* (1990), vol. **221**, pp. 553-576.

Anatol Roshko
Aeronautics Department 105-50
California Institute of Technology
Pasadena, CA 91125
(818) 356-4484

Date and Place of Birth:

[redacted] [redacted] [redacted] PII Redacted

Education

B.Sc. Engineering Physics, University of Alberta	1945
M.S. Aeronautics, California Institute of Technology	1947
Ph.D. Aeronautics, California Institute of Technology	1952

Academic Experience

Instructor (Mathematics) University of Alberta	1945–46
Lecturer (Engineering) University of Alberta	1949–50
Research Fellow (Aeronautics) Caltech	1952–55
Assistant Professor (Aeronautics) Caltech	1955–58
Associate Professor (Aeronautics) Caltech	1958–62
Professor (Aeronautics) Caltech	1962–
Theodore von Kármán Professor of Aeronautics	1985–
Acting Director, Graduate Aeronautical Laboratories, Caltech	1985–87

Consultant

McDonnell-Douglas Corporation
Rockwell International
General Motors Corporation

Professional Societies

U.S. National Academy of Engineering
American Academy of Arts and Sciences (Fellow)
Canadian Aeronautics and Space Institute (Fellow)
International Academy of Astronautics (Corresponding Member)
American Physical Society (Fellow)
American Institute of Aeronautics and Astronautics (Fellow)
Artic Institute of North America
American Association of University Professors
Sigma Xi
Wind Engineering Research, Inc. (Founding Director)

Fields of Interest

(1) Turbulent Shear Flow
(2) Separated Flow
(3) Transonic and Supersonic Aerodynamics
(4) Industrial Aerodynamics
(5) Effect of Wind and Ocean Currents on Structures

Committees, etc.

Associate Editor, Journal of Fluids and Structures	1986–
Technical Committee on Turbulence Engineering Mechanics Division of ASCE	1987–
Advisory Board Stanford/Ames Center for Turbulence Research	
National Research Council Aeronautics and Space Engineering Board	1988–
Associate Editor, Physics of Fluids	1971–73
Scientific Liaison Officer, Office of Naval Research, London	1961–62
National Science Foundation Exchange Scientist to India	1969
U.S. Wind Engineering Research Council Board of Directors	1978–85
Member National Committee for Theoretical and Applied Mechanics	1978–80
Fluid Dynamics Panel of AGARD	1984–89

Honors

Dryden Research Lecture, AIAA	1976
Turnbull Lecture, Canadian Aeronautics and Space Institute	1980
Fluid Dynamics Prize, American Physical Society Division of Fluid Dynamics	1987
Award for Professional Achievement, University of Alberta	1988
Opening Lecturer, XVIIIth International Congress of Theoretical and Applied Mechanics, Haifa	1992

DISTRIBUTION LIST

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